IMPROVED STRATEGIES FOR TRAFFIC RESPONSIVE CONTROL IN ARTERIAL SIGNAL SYSTEMS

BY

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LIST OF ABBREVIATIONS

AAP	=	Arterial Analysis Package
AVL	=	Arterial Volume Level
CALIFE	=	Computer Based Traffic Control System (Translated from French)
CHKINP	=	TRANSYT-7F CHKINP Subroutine
CAVD	=	Cross Street Arterial Volume Differential
FHWA	=	Federal Highway Administration
FORCAST	=	FORCAST Program
FPD	=	Flow Profile Diagram
GDF	=	Graphic Display File
HILLCL	=	TRANSYT-7F HILLCL Subroutine
INPTRN	=	TRANSYT-7F INPTRN Subroutine
INTEL	=	Intelligent Signal System
IOVD	=	Inbound Outbound Volume Differential
LLAVL	=	Low Limit of Arterial Volume Level
MCTRANS	=	Microcomputers in Transportation University of Florida
MOE	=	TRANSYT-7F Measures of Effectiveness
OPAC	=	Optimization Policy for Adaptive Control
PASSER-II	=	Progression Analysis and Signal System Evaluation Routine, version Two
PASSER-II[80]	=	1980 Version of PASSER-II program
PASSER-II[84]	=	1984 Version of PASSER-II program
PASSER-II[87]	=	1987 Version of PASSER-II program

PI	=	TRANSYT Performance Index
PPD	=	Platoon Progression Diagram
PROGO	=	PROgression Graphic and Optimization Program
SAS	=	Statistical Analysis System
SAS/IML	=	SAS Interactive Matrix Language
SCAT	=	Sydney Coordinated Adaptive Traffic
SCII	=	Signal Control of Isolated Intersections
SCOOT	=	Split Cycle and Offset Optimization Technique
SIGOP	=	Traffic SIGnal Optimization Model
SOAP	=	Signal Operation Analysis Package
SSTOP	=	Signal SysTem Optimization Package
SUBPT	=	TRANSYT-7F SUBPT Subroutine
TOD	=	Time of Day Selection of Timing Plans
TRANSYT	=	TRaffic Network StudY Tool
TRANSYT-7	=	TRaffic Network StudY Tool, Version 7
TRANSYT-7F	=	TRaffic Network StudY Tool, Version 7, Federal
Transyt 3800	=	Transyt 3800 Closed Loop System
TRSP	=	Traffic Responsive Selection of Timing Plans
TRUSTS	=	Traffic Responsive and Uniform Surveillance Timing System
TSD	=	Time-Space Diagram
T7F145	=	T7F145 Experimental Version of TRANSYT-7F
T7F245	=	T7F245 Experimental Version of TRANSYT-7F
ULAVL	=	Upper Limit of Arterial Volume Level
UTCS	=	Urban Traffic Control System

UTCS-1GC = Urban Traffic Control System, First Generation Control

UTCS-1.5GC = UTCS First and Half Generation Control

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IMPROVED STRATEGIES FOR TRAFFIC RESPONSIVE CONTROL IN ARTERIAL SIGNAL SYSTEMS

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Several types of real-time traffic responsive control strategies have been developed to select signal timing plans on-line. The goal has been to improve the traffic performance through implementation of plans which are more suited to prevailing traffic conditions. One type of such strategies uses preset transfer thresholds to select signal timing plans from a prestored library. These thresholds are currently specified by judgment.

This dissertation proposes a methodology for determining the transfer thresholds for a traffic responsive control strategy. The basic technique used is to evaluate each signal timing design under a range of traffic conditions using TRANSYT-7F. A design is selected for implementation under a given traffic condition if it produces the lowest TRANSYT-7F performance index compared to

the other designs. The methodology requires estimation of the turning movement volumes in the system based on detector measurements. Two models are developed for the purpose of volume estimation.

Problems are identified by the off-line signal timing programs used in this study. These programs are AAP, TRANSYT-7F, and PASSER-II. Since these problems affect threshold determination, an investigation of the problems is performed.

The application of the methodology proposed in this study to the determination of transfer thresholds should improve the system operation by replacing the element of judgment by a more objective technique. In addition, solving the problems identified by the off-line signal timing programs would improve the performance of these programs.

CHAPTER ONE
INTRODUCTION

An urban traffic control system is typically designed around a central computer which communicates by one of several means with individual intersections which are coordinated within the system. Detector and display information are received from the field and commands of one kind or another are returned to the field. The central computer may vary in size from a simple personal computer to a full-scale mainframe system.

Microcomputer based traffic control systems have become very popular in the United States. They are less expensive to install and operate than the more complex centrally controlled systems of the past decade. The use of personal computers with dial-up telephone communications provides a cost-effective method of supervising a large group of traffic signals. The traffic control industry uses the term, "closed loop system" as a generic reference to this concept. In the broad terminology of computerized traffic control, they are classified as "First Generation Systems" because they use a library of timing plans which were developed independently.

There are four basic operating modes for these systems:

1. The Free Running mode, in which all intersections, operate independently, typically used only under late-night, low-volume conditions.

2. The Time of Day or TOD mode, in which all intersections are coordinated based on timing plans which are switched at specific times of the day to accommodate known variations in traffic patterns.

3. The Traffic Responsive mode, usually denoted by TRSP, which is similar to the TOD mode except that timing plans are switched in response to measured traffic conditions.

4. The Manual mode, in which timing plans are switched by the system operator.

There is a certain amount of theory and probably an equal amount of practical judgment which apply to each of these modes. In the case of the TRSP mode, excessive practical judgment is required because of inadequate theoretical support. The development of a model to strengthen the theoretical basis for TRSP operation is the subject of this dissertation.

Need for the Research

The ultimate objective of the traffic control engineer is to utilize urban street networks efficiently through the use of effective control strategies. One of the most important steps in achieving this goal is the development of

computer-based traffic control systems. In those cities where computer based controls have been installed, traffic flow and operational efficiency have improved, and both fuel consumption and air pollution have been reduced (1,2).

Among the different forms of computer control, first generation control systems are the most commonly implemented because of their lower installation, maintenance and operating costs, together with their proven effectiveness (3,4). First generation control involves signal timing plans developed off-line by one of the optimization models and stored in computer memory as a timing plan library. The plan controlling the traffic system can then be selected on the basis of TOD, manual, or TRSP (3,5).

Because of day-to-day fluctuations in traffic patterns, traffic responsive control strategies are expected to provide a better match of plan-to-traffic conditions than simple TOD selection provides. However, TRSP strategies are considerably more expensive to implement than TOD strategies. TRSP requires the installation of detectors that are capable of providing an early identification of traffic trends within the system (6). In addition, it requires the transmission of detector information to the control computer. This increases the communication cost. Thus, the primary requirement of any traffic responsive strategy is that it must provide better performance than off-line methods (7).

At the present time, there are several limitations to traffic responsive strategies which reduce their effectiveness. Although the timing plan design models, such as TRANSYT-7F[1] (TRAffic Network StudY Tool, version 7, Federal) (8) and PASSER-II (Progression Analysis and Signal System Evaluation Routine, version Two) (9), are adequate and can create an acceptable timing plan library, there are still problems associated with the implementation of these timing plans in a traffic-responsive mode.

Generally, the TRSP timing plan selections in First Generation Control (1GC) are of two types. In the first type, the timing plans are selected based on the value of a comparison function. The function is calculated based on detector measurements and compared with prestored values to determine which plan should be implemented. The timing plan selection in the Urban Traffic Control System first generation control (UTCS-1GC) is an example of this type of selection (5). In the second type, preset transfer thresholds are employed to decide which timing plan should be selected for implementation. This type of timing pattern selection is used in some types of closed loop systems (3). Several areas of potential improvement can be suggested for both types of timing plan selection.

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[1]In this dissertation the word "TRANSYT" refers to the TRaffic Network StudY Tool (TRANSYT) often followed by an extension (e.g., "-T7F") to indicate a specific version. "Transyt" refers to the Transyt Corporation which manufactures a closed loop traffic control system.

Currently, the timing plan change thresholds are specified by judgment in those systems that employ thresholds in timing pattern selection. No research has been done in the area of threshold determination.

Any signal timing plan selection strategy (on-line or off-line) tries to achieve a certain objective when selecting the plans. This objective varies from one strategy to another. For example, it could be maximizing the progression efficiency or minimizing delays and stops. The engineering judgment is not enough to decide the timing plans that are capable to achieve this goal. Thus, the thresholds should be selected through some objective technique. The use of judgment to select thresholds may give rise to the selection of plans which are not the best for the conditions measured through the traffic detection system.

There exists, therefore, a clear need for the development of models to improve the timing selection of the TRSP control in an arterial signal system.

Objective and Scope

The goal of this study is to improve the timing plan selection process in computer based traffic control systems.

This study presents a methodology for determining the transfer thresholds for the TRSP mode of operation of a computer based traffic control system. This methodology requires the estimation of the turning movement volumes in the system based on detector measurements. For this

purpose, off-line signal timing programs should be used to design signal timing plans for the TRSP operation and to evaluate these plans. Problems have been experienced with these off-line programs. It is thought that these problems might affect the results obtained from this study.

This research deals primarily with coordinated traffic signal systems on arterial highways. The models developed are limited to recurring operations and normal weekday variations in traffic flow. Thus, other timing plans based on judgment may still be required for handling unusual traffic conditions. In addition, the models developed in this study require the availability of reliable field traffic data.

The specific objectives of the study are:

1. Review the literature with respect to subjects which are pertinent to this study.

2. Develop models to estimate the turning movement volumes at each intersection in the system based on detector measurements.

3. Develop a method to determine the thresholds for switching between timing plans in a specific closed loop system. The quality and quantity of detector information available from a typical closed loop system are not adequate to support a complex model of the operation. It is, therefore, not realistic to seek results which can be demonstrated to be globally optimum from a mathematical point of view.

A more realistic objective would be to improve the design results by replacing the element of judgment by a more objective technique based on system models.

4. Investigate probable problems and inconsistencies in those off-line signal timing models which are used in preparing the timing plan libraries.

The models developed in this study should be based on well developed theories. In addition, the off-line signal timing models used for design and evaluation of timing plans are among those most accepted by the traffic engineering community.

There are some operational differences between different closed loop systems. The models described herein are generic in nature to the extent possible. The application of these models must, however, be tailored to a specific type of system. The system chosen for this study was the system which has been installed in Gainesville, FL. This system is a Transyt 3800 closed loop system. This is the predominant type of closed loop system used in Florida. The University of Florida Transportation Research Center has a terminal linked to the Gainesville system operating in its Traffic Control System Laboratory.

Organization

This dissertation is structured according to the objectives stated earlier. The next chapter consists of a review of the literature that is pertinent to this study. First

the different types of computer based traffic control strategies are discussed. Then, a review of timing plan selection in 1GC is presented. Next, a literature review of the estimation of nondetectorized traffic volumes and the balancing of input/output flows in a system is presented. All of these subjects are pertinent to the models developed in this study.

Chapter Three presents a method for obtaining the transfer thresholds using an estimated variation model to determine the turning movement volumes in the system from detector volumes.

Chapter Four presents an assumed variation model as a simplified alternative to the estimated variation model. The use of this model in the transfer threshold determination is also discussed.

Chapter Five investigates some of the problems experienced with the off-line signal timing models used to design and evaluate the signal timing plans in this study. Some of those problems were addressed in experimental versions of the programs.

Finally in Chapter Six are the conclusions and recommendations obtained from this study. The conclusions summarize the findings. The recommendations include four areas: improvements in the TRSP strategy investigated, further improvements in threshold determination methodology, treatments of problems identified in the off-line programs,

and further research required for the TRSP selection of timing plans.

CHAPTER TWO
LITERATURE REVIEW

Basic Concepts of Signal Timing

A basic understanding of the concepts of signal timing is a prerequisite to the discussion presented later in this dissertation.

The concepts of signal timing are well documented in the literature. Some of the basic definitions are presented below for convenient reference (3).

Cycle length. The number of seconds required for a signal to display its entire sequence of indications and return to its starting point.

Interval. A discrete portion of the signal during which the signal indications (pedestrian or vehicle) remain unchanged.

Offset. The time relationship expressed in seconds or percent of cycle length, determined by the difference between a system time reference point and a specific interval in the sequence.

Phase. The portion of a signal cycle allocated to any single combination of one or more traffic movements simultaneously receiving the right to proceed, subject to other rightful movements, during one or more intervals.

Sequence. A predetermined order in which the phases of a cycle occurs. Some controller units have skip-phase capability. Full actuated traffic control provides an example of skip-phasing. In this type of control, it is possible to skip phases when no traffic is present and to terminate certain movements as soon as the traffic on that movement has been moved into the intersection.

Split. The percentage of a cycle length allocated to each of the various phases in a single cycle. In pretimed controls, the splits are fixed, while in actuated controls, the splits are adjusted continuously in accordance with detector measurements.

The traffic flow control concept for arterial streets can be represented graphically by a technique known as a time space diagram as shown in Figure 2.1. A time space diagram is a two-dimensional representation of (a) the spacing of the various intersections along the artery, and (b) the signal indications at each of these intersections as a function of time.

In the diagram, a "band" of green time is propagated through the system such that vehicles traveling within its limits progress throughout the system without being stopped. A through-band is defined as the time between a pair of parallel speed lines which delineates a progressive movement in the diagram. The bandwidth is defined as the width of the through-band in seconds indicating the period of time

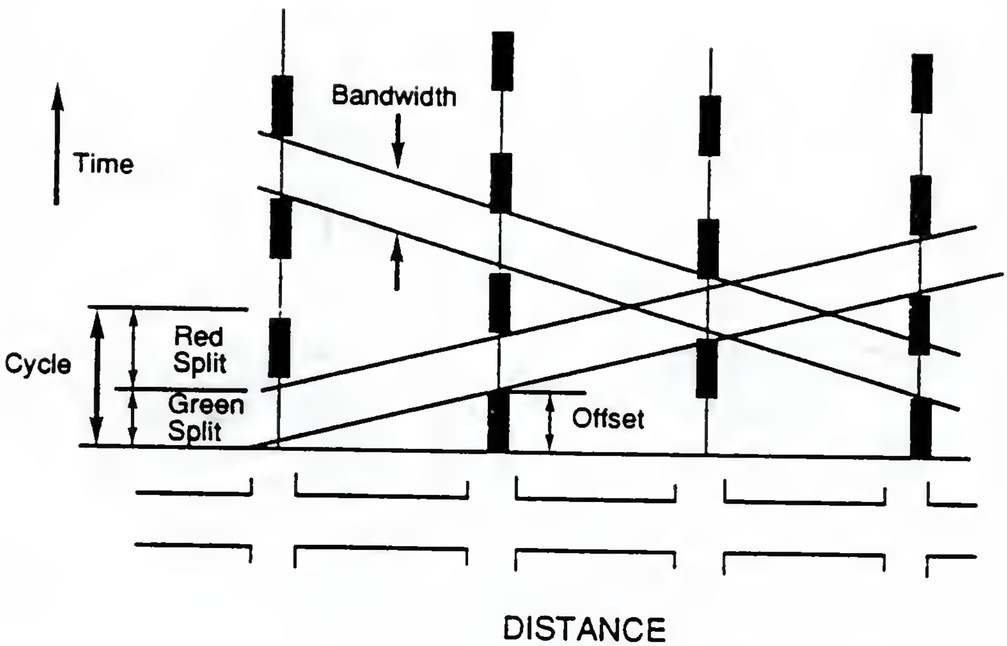

Figure 2.1. A time space diagram illustrating the signal progression control concept for arterial streets.

available for traffic to flow within the band. Wider bands produce better operations as perceived by the drivers.

Review of Computer Based Traffic Control Strategies

Strategies for the on-line computer-based control of traffic signals have become increasingly important in recent years. Several types of computer--based traffic control systems have been developed and implemented throughout the world. Experiences with these systems have demonstrated their capability to produce considerable improvements in traffic operations (10).

The discussion presented in this section is organized such that the 1GC strategies which have a lower degree of traffic responsiveness among the real-time traffic control strategies are discussed first. Then the attempts to develop strategies with higher degrees of traffic responsiveness are discussed.

As mentioned in Chapter One, several computer based traffic control systems can be classified as 1GC. UTCS-1GC[2], and all types of closed loop systems can be classified as 1GC.

The 1GC systems use prestored traffic signal-timing plans developed off-line and based on previously collected

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[2]Different Urban Traffic Control System (UTCS) strategies have been developed by the FHWA. Each strategy is referred to as a generation. The higher the UTCS generation number, the more it is responsive to traffic conditions. All UTCS generations will be discussed later in this section.

traffic data. Timing plans can then be selected on the basis of TOD, operator selection or TRSP selection. In the TRSP mode of operation, the timing plans are selected based upon traffic conditions which are measured through a traffic detection system.

In the United States, the predominant on-line control strategy has been that of the UTCS-1GC developed by the Federal Highway Administration (FHWA) (1,5).

The UTCS-1GC performance was evaluated in Washington, DC (11) and New Orleans, LA (12). In its various modes of operation the UTCS-1GC performed better than a well-timed three-dial system.

UTCS is a centralized computer control system. Centralized systems are characterized by having all of the decision-making and surveillance capabilities located at one geographic point and on one level. The central computer processes all data and controls all signal phases. The basic configuration of a UTCS system is illustrated in Figure 2.2. Problems such as limited capacity, high communication cost, and low flexibility were identified with such types of controls (13,14).

Closed loop systems have become very popular in recent years. They avoid many of the problems associated with the centrally controlled systems by using the decentralized concept of control. In this concept (10,13), the control logic and the surveillance capability are decentralized from

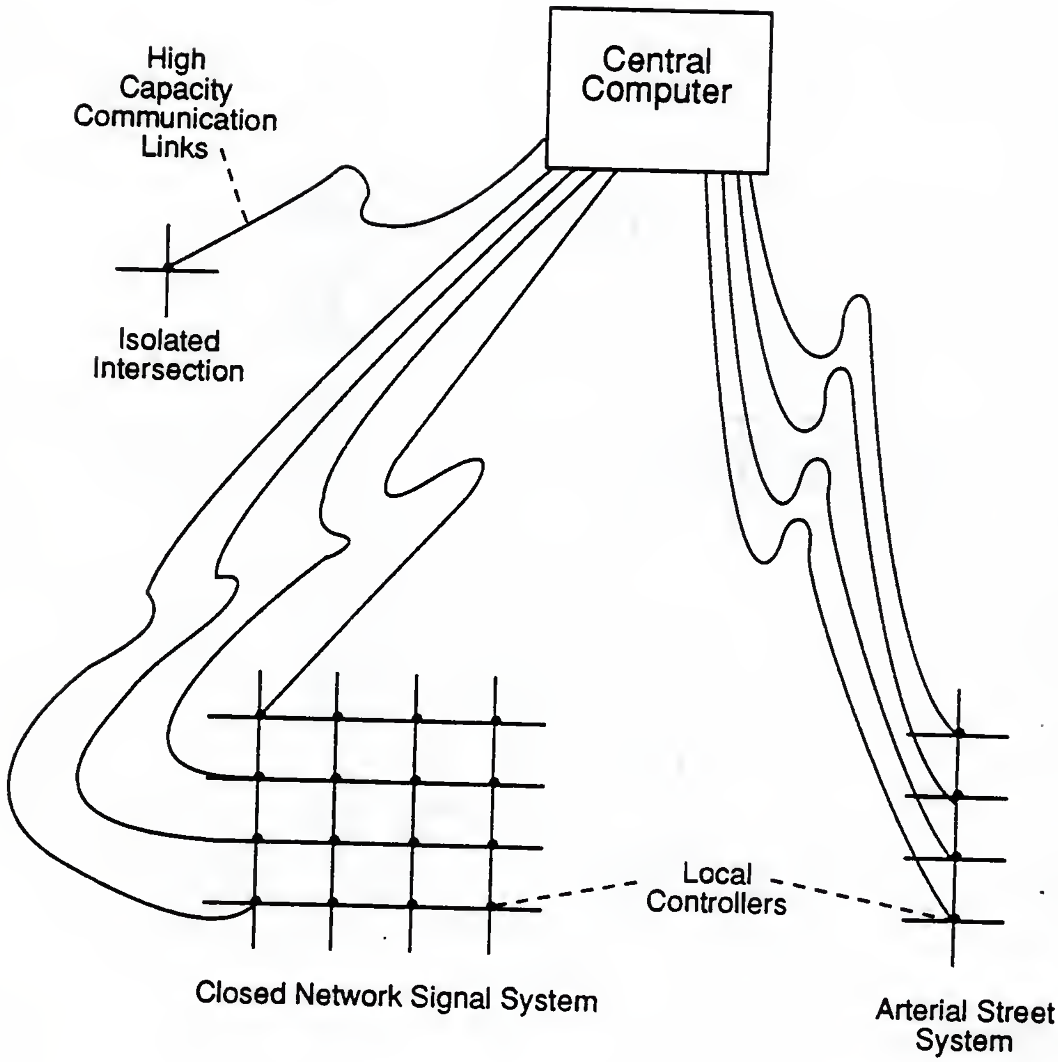

Figure 2.2. The basic configuration of a UTCS system.

NOTE: Communication links connect each local controller in the closed network signal system with the central computer. In this figure, only some of these connections are shown for simplicity.

a geographic viewpoint and placed at various levels in hierarchial organizations of surveillance and control functions. The basic configuration of a closed loop system is presented in Figure 2.3.

Although the original concept of closed loop systems was developed in the mid-seventies, the technology available at that time could not support it. However, it has become more attractive with the rapid development in microcomputer technology in the eighties.

A typical closed loop system consists of a central computer, on-street microcomputer masters, two-way communications, local controllers and subsystem detectors (3,15). The role of the central computer in closed loop systems is different from that in UTCS. In closed loop systems, the tasks performed by the central computer are reduced significantly. The central computer role is limited to performing such functions as system monitoring, uploading and downloading of data, and data base storage.

The on-street master has the ability to select one of its stored signal timing plans. It then commands the local controller to implement the pattern chosen. The local controller units usually have time-base backup capability.

Continual on-line interconnection between the central computer and the on-street master is not needed. Thus, telephone dial-up or direct telephone lines can be used between the two. However, a higher capacity mode of

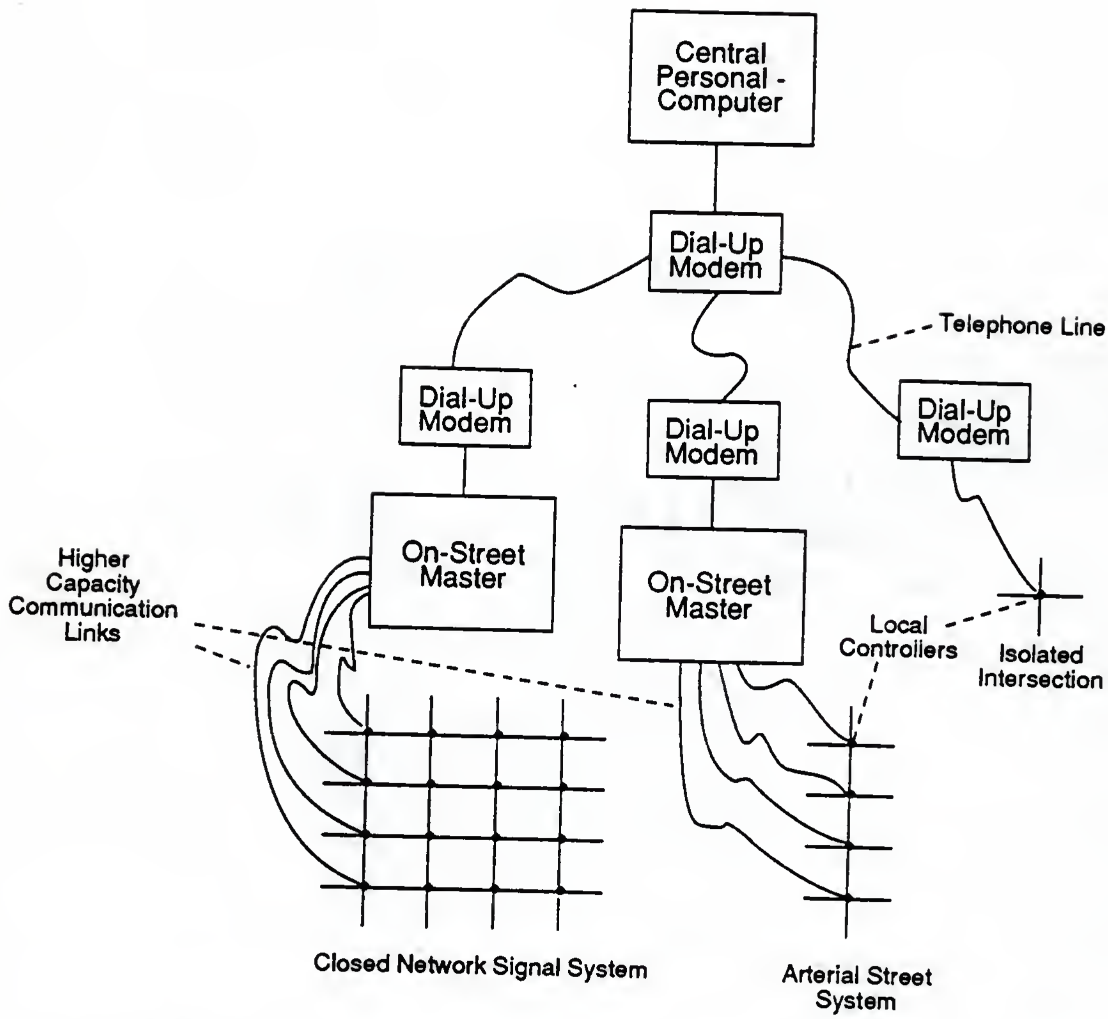

Figure 2.3. The basic configuration of a closed loop system.

NOTE: Communication links connect each local controller in the closed network signal system with the central computer. In this figure, only some of these connections are shown for simplicity.

communication is required between the master and local supervisors (3,15).

Closed loop systems are applicable to a wide range of geographic configurations such as arterials, grids, and area-wide control. Some of the advantages of such systems over the centralized systems are (10,13):

1. A reduction of the overall costs of the control system by decreasing the communication cost. This is because direct communication between the central computer and local controllers requires the UTCS to depend on a complex, more expensive dedicated communication system. In closed loop systems cheaper modes of communication can be used between the central computer and on-street masters.

2. An improvement of total system reliability by making it insensitive to failures of a single decentralized computer. The system is not dependent on one central computer or central communications gear.

3. A greater capacity to handle real-time elements (detectors, local controllers) that must be supervised or controlled.

4. An increase in the flexibility of the system structure. The system design permits future expansion without major modification to existing hardware.

Several types of closed loop systems have been developed in the 1980s. These systems differ from one another in specific control and surveillance features (3). In spite of

their differences, all of them can be classified as 1GC systems. In all types, the signal timing plan selection is made from a prestored library of signal timing plans.

Off-line optimization programs are used to generate timing plans for the first generation control strategies. There are two basic approaches for off-line optimization of arterial timing: (a) minimizing overall delay and stops, and (b) maximizing the bandwidth efficiency which is the percentage of the cycle available for progression. TRANSYT-7F and PASSER-II, the two programs described in this section, are among the models most widely used for signal timing optimization of arterial streets.

The TRANSYT model consists of two main parts (8).

1. A traffic flow model which is a deterministic macroscopic time scan simulation. It simulates the traffic flow in a given signal system to compute the performance index (PI) for a given set of signal timings. The PI is a weighted sum of stops and delays.

2. A hill-climbing optimization procedure which makes changes to the signal timings and determines whether or not the PI is improved. By adopting only those changes that reduce the PI, the optimizer tries to find a set of timings which makes the PI as small as possible, subject to the limit placed on the process.

Although there is no guarantee that the global optimum will always be found, TRANSYT-7F should always produce a good signal timing plan.

PASSER-II (9) is a macroscopic optimization model based on the maximal bandwidth efficiency principle. It provides the best phasing sequence and offsets for maximal bandwidth efficiency along the artery by minimizing the sum of interferences to the through bandwidths. The optimal cycle length is determined by means of an exhaustive search of all user-allowed values. Splits are calculated for minimum delay at each intersection on the basis of a modified Webster delay formula (16). The model also allows for variations in the overall progression speed and weighting of the directional bands.

One of the problems associated with 1GC systems is the high cost of preparing and updating timing plan libraries. This results in the implementation of out-of-date plans which may not be well-matched to the current flow patterns (17). An UTCS control strategy referred to as UTCS first and half generation control (UTCS-1.5GC) has been developed to solve this problem. This strategy automates the timing plan development task to the maximum extent possible. The system regularly (e.g., every six months) tests the timing plans that are being used against new plans calculated from the automatically collected traffic volumes. When it appears that traffic has changed to a point where a new plan

is warranted, the plan is developed and implemented using the computer-aided techniques (18,19).

The new plan can be prepared using any timing plan generator. FORCAST (20,21) is one of the programs that has been used for this purpose. FORCAST executes quickly and thus is well suited for on-line use. It performs an iterative search for optimum timing plans over a range of cycle lengths. In this process, each of the permitted cycle lengths is examined and a best timing plan is developed which corresponds to this cycle. The optimization logic involves sequential threading of prescribed movements through the network using a priority listing of demands to be accommodated. During this process, FORCAST adjusts the individual splits and offsets of the intersections so as to accommodate best the defined movements which pass through the network. FORCAST computes the cost associated with stops and delay and selects the timing plan by choosing the minimum cost solution.

It is possible to replace FORCAST by any timing plan generator. For example, TRANSYT could be used if the computer system has enough memory and the processor is of high enough speed. Three programs were investigated for this purpose (18). These programs were TRANSYT-7F, the traffic SIGnal OPtimization model (SIGOP) and the Signal SysTem Optimization Package (SSTOP). It appeared that TRANSYT-7F was the most suitable program based on the quality of the

timing plans it produced and its insensitivity to errors in the input data.

Several attempts have been made in different countries to develop systems which have higher degrees of traffic responsiveness than the 1GC and the UTCS-1.5GC strategies. In these systems, the signal timing plans are generated on-line based on detector measurements.

It was expected that these systems would produce better results than 1GC, which selects the signal timing plan from a library generated off-line, based on historical data from another month, perhaps another year. However, many of the attempts to develop such systems failed to produce good results. In the United States, second and third generation control strategies were developed and tested under the UTCS research project conducted by the FHWA (1,5).

The second generation control strategy is a real-time on-line control wherein timing plans are computed and implemented periodically. This type of control is based on a background cycle but provides for real-time computation of timing plans. It utilizes a prediction model to predict near-term changes in traffic conditions. These predictions are then used in an optimization model to develop the timing plan. The optimization model used is that of the SIGOP program.

The third generation control strategy was developed to implement and evaluate a fully responsive on-line traffic

control system. The cycle length, offset and split timing plan for each controller were permitted to vary from cycle to cycle. The increased complexity of the second and third generation control required additional detectors and more computer time and memory compared to the 1GC. The evaluations of the two strategies revealed that both were inferior to the 1GC strategy and that the third generation control seriously degraded traffic flow under almost all the conditions for which it was evaluated (1,5). Thus, neither strategy proved workable under the development budgets provided and appeared to offer insufficient promise to warrant further FHWA investment at the time (19).

Several systems (22,23) were also designed and tested in Great Britain, Canada, and Spain during the late sixties and early seventies to move from the 1GC type of control towards more flexible approaches which generate signal timings in real-time. These attempts proved to give similar or worse results than a well-optimized three-dial system (22,23).

Lack of success in those early attempts in the United States and in other countries has been related to a number of factors which include (7,19,22)

1. Even the best methods of plan changing cause significant transition delay, so frequent plan changing should not be considered.

2. A prediction of traffic flow for several minutes into the future is necessary when implementing those strategies. The random variation in traffic makes this prediction very difficult and some historical data are needed to help identify trends. Large discrepancies were observed (occasionally in excess of 50%) when comparing the performance of the UTCS second- and third-generation predictors with actual volumes over successive five-minute intervals.

3. When an unexpected event occurs, the response is delayed by the historical element of prediction and the need for a new plan.

4. Poor plans might be implemented due to faulty detectors or unexpected events which cannot be corrected until the next plan update.

5. In such systems, a large number of detectors has to be installed and maintained. Detectors have proved to be one of the less reliable components of many systems and the installation and maintenance costs of the detection systems are significant.

In spite of the failure of these early attempts, the work to develop new systems which are more responsive to current traffic conditions has continued. Some of these new systems use versions of the available off-line signal optimization programs to calculate signal timing plans on-line. Others adjust the signal timing in real-time, responsive to changes in traffic conditions. CALIFE (24)

and Traffic Responsive and Uniform Surveillance Timing System (TRUSTS) (25) are examples of the first type. Split, Cycle and Offset Optimization Technique (SCOOT) (26), Sydney Coordinated Adaptive Traffic (SCAT) (27) and Optimization Policy for Adaptive Control (OPAC) (23) are examples of the second type.

CALIFE is a system developed in France. This system (24) utilizes a modified version of TRANSYT-7 to calculate on-line the signal timings based on traffic flows derived from a prediction model. Two modifications were made to TRANSYT-7: (a) A preliminary cycle search was first made in which no offsets and splits optimization was made. At this stage, the green times are simply set to give equal degrees of saturation on the critical links. (b) A supplementary term was added to the performance index of the TRANSYT-7 optimization procedure. This term, the transition criterion, was meant to take the proximity of the new plan into account in relation to the present one. In this manner, the transition delay between successive plans was reduced.

Simulation results showed that significant savings can be obtained with CALIFE compared to the classical 1GC.

TRUSTS is a microcomputer based on-line traffic control system developed recently in Taiwan (25). The system offers the user the choice of on-line timing plan generation, on-line timing plan selection or time-of-day timing plans. The

on-line timing plan generation uses a modified version of TRANSYT-7F, a maximum progression bandwidth program (BANDTOP) or a combination of both programs.

Two traffic responsive systems with a high level of traffic adaptability are currently employed for daily use in a number of cities. These two systems, SCOOT and SCAT, were developed in Great Britain and Australia, respectively. The two systems implement frequent but small changes in cycle time, phase splits, and offsets to cope with the rapid fluctuations of traffic demand. Both methods abandon the prediction of traffic flow as a mean of controlling traffic.

SCOOT (26,27) is similar to the TRANSYT program in the principle of optimization. A fundamental component of TRANSYT is the traffic flow profile. SCOOT uses information from vehicle detectors to obtain the profiles in real time. Together with preset saturation flows and link travel times, these profiles are used to predict the queues at the downstream intersection. SCOOT operates groups of adjacent intersections on a common cycle time. The signal optimizer adjusts the signal timings in small steps to reduce the total delay and stops in the system (26). Also, there are special procedures in SCOOT to deal with congestion. The SCOOT system has been tested and evaluated in a number of field trials. The trials show that, on average, SCOOT reduces the delay to vehicles by 12% when compared to fixed

time control using up-to-date plans calculated employing TRANSYT (26).

The most important parameter used by the SCAT algorithm (27,28) is one analogous to the degree of saturation. It is defined as the ratio of the effectively utilized green time to the total available green time. In this system, the cycle length is updated each cycle in steps of up to six seconds according to the degree of saturation of the system. To select green split plans, once per cycle, a split plan vote based on the degree of saturation is calculated. Two votes for the same plan in any three consecutive cycles result in the selection of the plan. The offsets are also selected based on an offset plan vote which is based on directional splits of traffic flow. SCAT was found to result in similar performance to fixed-time control in travel time, but was 9% better in stops in the total survey period (27). The field surveys conducted indicated that there are periods during which fixed-time control actually performed better than either SCAT or SCOOT (27).

OPAC is a real-time demand-responsive system developed in the United States. The system was designed with a high degree of adaptiveness to traffic conditions (23). The real-time optimization procedure in OPAC is based on a "pseudo-dynamic programming technique." The optimization process is divided into sequential stages of time intervals (in the range of 50 - 100 seconds). During each stage there

is at least one signal change (switch-over) and at most three switch-overs. Then, an objective function (total delay) is evaluated sequentially for all feasible switching sequences and the optimal sequence is selected. Simulation testings of the OPAC strategy showed that it is capable of providing better performance than other forms of signal control (29). OPAC was also field tested in two locations. The results showed that significant improvements can be obtained when compared with existing traffic-actuated methods. Average delays were reduced by 5% to 15%. Most of the benefits occurred in high volume/capacity conditions (29).

One of the latest fields of research in the subject of real-time control is the attempt to develop on-line control strategies that use expert systems to decide about the signal timing pattern under the circumstances. The Intelligent Signal System (INTEL) (30) and the Signal Control of Isolated Intersections (SCII) (31) are two examples.

An expert system was also used in the TRUSTS system discussed earlier, to determine the appropriate type of operational mode to use under current traffic conditions (32). As described previously, TRUSTS provides three modes of operation: TOD, on-line plan selection, and on-line plan generation.

The use of machine vision to detect traffic events in control is another promising field of research. Several

problems are associated with the use of the existing type of detectors (i.e., loops) in traffic responsive control. Such detector types have limited capabilities, present reliability problems, and require massive and expensive installation for true traffic responsive control. Recent advances in image processing and understanding, electronic cameras, special purpose computer architecture and micro-processor technology have made the machine vision alternative for vehicle detection attractive, economical and promising (33).

Timing Plan Selection in First-Generation Control

As stated earlier, in 1GC systems, the timing plans can be selected on the basis of TOD, TRSP or manual.

Jrew and Parsonson (34) studied a technique for determining the best time to change timing plans in the TOD operation of a computerized traffic control system. The study examined the use of several off-line programs to determine the time to change from the off-peak timing plan to the peak-period timing plan in an arterial system. The use of PASSER-II[80][3] for plan designs was considered unsuccessful because it was found that both periods required the same cycle lengths. Thus, TRANSYT-7F was used to design

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[3]The number between brackets following PASSER-II refers to a specific version of the program. In this dissertation, when the version is not specified following the PASSER-II term, it means that the reference is made to PASSER-II[84] which is the 1984 version of the program.

timing plans for the off-peak and the peak periods. TRANSYT-7F simulation runs were then performed to determine the performance of the two plans for each 15-minute interval during the afternoon. The results were used to plot the PI of the two plans versus the time of day. The intersection of the two curves was selected to be the time to change plans. To reduce the computer time, the possibility of using the Signal Operation Analysis Package (SOAP) to determine the time to change plans was investigated. It was theorized that the TRANSYT-7F procedure might be replaced by a relatively simple SOAP analysis at only the critical intersection. However, it was found that during all times during the afternoon the off-peak cycle length performed better. Therefore, the SOAP analysis failed to produce an optimal time to change the plan (34).

In implementing the TRSP mode of the 1GC, timing plans are selected based on traffic conditions which are measured through a traffic detection system.

Although many systems can be classified as 1GC, the algorithms used in timing plan selection vary from one system type to another. Generally, the base flow parameters used in the selection are the volume, the occupancy or a combination of the two. The volume and the occupancy are

measured by system sensors[4] and are fed into the control computer for the plan selection purpose. Occupancy is defined as the percent time that the detector is indicating a vehicle presence measured over a total time period. Volume and occupancy are used in timing plan selection due to their ease of measurement, their accuracy and their sensitivity to traffic demand (5).

In many instances, volume can be used without occupancy. However, when the intersection approaches saturation, volume will level off to a constant value that is proportional to the available green time divided by the average vehicle headways, while occupancy will continue to increase (4). If this condition persists, long queues develop and may reach from one intersection to another. When this occurs, traffic is unable to move even when it receives a green light and traffic jam conditions result. Thus, the advantage of using occupancy is that it will reflect congestion on the link more accurately.

Bell and Gault (35) used volume as the base flow parameter to determine the flow level at which it is most efficient to change signal timing plans. TRANSYT-7 was used to calculate performance indices for the peak and off-peak plans for a range of average flows. A plot of PI versus

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[4]System sensors are defined as traffic detection devices (detectors) that permit the system master to obtain information as to the traffic flow characteristics in the area of the sensor.

flow was prepared for each plan. The flow level at which the two curves crossed each other was regarded as the best level to transfer from one plan to the other.

Taylor (36) tested systems that identify the beginning of successive peak and off-peak conditions by comparing the detector output with predefined parameters derived from historical data. A simulation study was conducted to compare the use of three flow parameters for this purpose. The three parameters used were volume, occupancy and volume-to-occupancy ratio. The volume was used in the same way as that used by Bell and Gault (35) as explained above.

The use of occupancy to decide when to change plans was more complex than using volume. Field surveys were necessary to define the critical occupancy level prior to the installation of the system. Occupancy was plotted as a function of volume and the occupancy levels relating to the critical flow levels were derived. These values were used as the occupancy based thresholds for changing plans.

The third parameter used was the volume-to-occupancy ratio. The volume and occupancy were linearly related under unsaturated conditions, thus the ratio between the two was constant. However, the onset of peak conditions disrupted free flow and the ratio changed. From examining the plot of ratio against flow, a level of ratio was defined at which the plan change should occur. This level was considered to be the one at which the ratio became a function of flow.

The study concluded that, under simulation conditions, there was no difference between the three strategies tested. However, volume-to-occupancy ratio was recommended for use because it is more likely to remain stable through short-term flow disruptions and would be less likely to cause unnecessary plan changes.

Most of the work concerning the TRSP plan selection of the 1GC in the United States has been concentrated around that of the UTCS-1GC.

The traffic flow parameter, used for the timing plan selection in the UTCS-1GC strategy, is a combination of volume plus weighted occupancy (37). Corresponding to each timing plan, there is a prestored signature which is the design value of the traffic flow parameter for the plan. In the TRSP operation, for each time interval, a flow parameter index is derived from field detector data as follows

$$I_{it} = VOL_{it} + KO \bullet OCC_{it} \tag{2.1}$$

where

I_{it} = the measured flow parameter index for detector i and interval t,

VOL_{it} = the smoothed volume for detector i and interval t,

OCC_{it} = the smoothed occupancy for detector i and interval t, and

KO = the occupancy weighting factor.

The deviation of each signal timing plan signature from the flow parameter index for a time interval t is calculated using the following comparison function

$$T_{jt} = \sum_{i=1}^{L} W_i \mid I_{it} - S_{ij} \mid \tag{2.2}$$

where

T_{jt} = the value of pattern recognition function associated with timing plan j at time interval t,

W_i = the weighting factor for link i,

S_{ij} = the signature of link i associated with timing plan j, and

L = the number of detectorized links in the section.

The plan with the minimum recognition function is considered for implementation. Minimum time between changes and minimum threshold criteria are established by the operator to prevent excessive switching between timing plans.

The occupancy weight (KO) used in the calculation of the base flow parameter in equation (2.1) is selected to scale the occupancy term to a magnitude which is comparable to the volume term. The traffic volume ranges theoretically from zero to 2000 vehicles per hour per lane. However, the occupancy, in percentage, ranges only from zero to 100. Thus, it is necessary to adjust the magnitude of the occupancy so that the occupancy is not suppressed by very

large traffic volumes. Twenty is the value that is frequently used because it causes the magnitude of the occupancy to approximate the magnitude of the volume when the system is approaching saturation (5).

A theoretical study (4) indicated that there is some skepticism about the effectiveness of using the flow parameter index (I_{it}) in the deviation computation. It was suggested that using the index will hinder the effectiveness of the current selection algorithm under congested traffic conditions. The study suggested that the occupancy information should be fully utilized, to describe congested conditions, instead of combining it with the volume to form a single flow parameter. For this purpose, a modification of the comparison function was suggested.

The study also questioned whether the constant weight applied to all occupancy data is appropriate with respect to selecting the correct timing plan (4). It was suggested that the weight should be determined for each link individually. A constant weight cannot be used since there is no direct linear relationship between volume and occupancy. Occupancy weights based on the volume density relationship were suggested.

Another study (38) investigated the effect of the occupancy weighting factor upon the performance of UTCS-1GC traffic responsive operation. A simulation study was used for this purpose. The study found that, for the range of

conditions studied, the value of the occupancy weighting factor had little effect on the performance of the UTCS-1GC traffic responsive operation. However, the network investigated operated under uncongested flow conditions. The volume and occupancy relationship is nearly linear under these conditions. Therefore, the inclusion of occupancy in the pattern recognition function provides no more information to the timing plan logic than volume alone. Further work is required to investigate the effect of the occupancy weighting factor when the network is operating under congested flow conditions.

As stated earlier, all closed loop control systems can be classified as 1GC systems. However, timing plan selection algorithms in these systems vary from one system to another. Volumes and occupancy, as measured by system sensors, are used differently to decide which timing plan should be implemented for a given traffic condition (3). This makes research in the field of improving the timing plan selection process in 1GC systems more difficult. The work conducted on a specific system type might not be applicable to another.

In Florida, the predominant type of closed loop system has been the Transyt 3800 closed loop system. When comparing the timing plan selection algorithm used by this system with that used by the UTCS-1GC, two major differences are apparent. Instead of selecting a whole timing plan, the

closed loop system selects the cycle, the offsets, and the splits separately in the TRSP mode of operation. Also, instead of using a pattern matching technique for the selection, the closed loop system control logic employs transfer thresholds to determine the set of signal timing parameters that is best suited to the measured traffic conditions (15).

The pattern selection routine of the system includes traffic flow analysis in three different areas: volume level of arterial traffic for cycle length selection, directionality of arterial traffic for offset plan selection, and arterial traffic to side street traffic differential for split plan selection.

The transfer thresholds based on volume calculations in these areas are entered as percents. Therefore, a base or a reference volume must be obtained first for the volume in each movement direction entered in the calculation. The volume level in a given direction is expressed as a percentage of the reference volume in that direction.

The arterial volume level used in cycle length selection is the inbound or the outbound volume level, whichever is higher. The master selects one of four cycle lengths or free operation. The transition points in volume levels for change to the next higher or lower cycle length are all programmable.

The master can select as many as five different offset plans. Offset plans are chosen based on the differential between inbound and outbound volume levels. The system provides the standard inbound, standard outbound and average offset plans but also offers heavy inbound and heavy outbound offsets if required.

The selection of system split plans is based on the differential between the side street volume level and the arterial volume level. Again, the arterial volume level is the maximum of the inbound and the outbound volume level. The system can provide three split plans.

The threshold volume level required to go to a new parameter design plan and the level required to leave that design to go back to the original design should be set somewhat apart to prevent cycling between plans.

Special patterns selected based on occupancy and queue can be set to override the patterns selected based on the normal traffic responsive operation described above. These special patterns are used to take into consideration the situation when the traffic within a system approaches saturated conditions. Two patterns can be selected based on occupancy and another two can be selected based on queue detector inputs. The patterns based on queue detectors override the patterns based on occupancy measurements.

As stated previously, under late night low volume conditions, computer based traffic control systems can

operate in the free running mode. In this mode, all intersections operate independently.

Luh and Courage (39) presented a method of facilitating the choice between coordination and free operation on arterial roadways controlled by semi-actuated signals when traffic is light during off-peak hours. The decision was made based upon a disutility function which is a combination of the number of stops on the artery and the average cross street waiting time.

Estimation of Nondetectorized Flows

TRSP control strategies need on-line information concerning traffic over the network. One obvious requirement for an effective TRSP control strategy is the establishment of a reliable surveillance system. However, we cannot expect every link in a system to be detectorized because of the high cost of detector installation and maintenance.

In many situations, we need to estimate traffic conditions at nondetectorized links from information obtained at detectorized links.

In an evaluation study of the UTCS-1GC system (12), the volumes on nondetectorized links and links with failed detectors were needed. These links were matched with "surrogate" detectors located on a link with similar geometric and traffic demands. A surrogated detector for a link was located within one block of the link with no detector.

In the UTCS-second generation control strategy, the timing plans are optimized on-line using the optimization model of the SIGOP program. This model requires the volumes and speeds on all links in the system, not just at those locations where detectors have been installed. Two alternatives were used to estimate the volumes on the non-detectorized links (5). These two alternatives were either to use historical (time-of-day) volumes and speeds for nondetectorized links or to assume that some combination of upstream and downstream measurements can be extrapolated to estimate the volumes on the nondetectorized links. In the first case, estimates of the time-of-day volumes (guesses by the traffic engineer) were saved. In the second case, time-of-day multiplying factors (also guesses by the traffic engineer) must be saved, representing the relationship between the volumes on the adjacent links.

Kell and Fullerton (19) tested the validity of using automatically collected traffic volumes from selected system detector sites to generate a full TRANSYT-7F input file for calculating signal timing plans in the UTCS-1.5GC. This approach assumes that volume shifts on selected links accurately represent shifts throughout the network. Site-specific algorithms were devised to synthesize the required TRANSYT-7F data from the system detector data. The optimum signal timing plans calculated based on these data sets

compared favorably with the optimum plans produced based on full TRANSYT-7F data (based on field-collected data sets).

The rules used to estimate the turning movements in the network in that study, were selected individually for each link in the network by the system traffic engineer. They were used to update traffic volumes for each time period based on detector data. Five rules were used, depending on the availability of detector data. These rules are listed below in the order of preference.

Rule 1: Traffic volumes for a given link were calculated based on detector data for that link.

Rule 2: Traffic volumes for a given link were calculated by summing projected input volumes from upstream links.

Rule 3: Traffic volumes were calculated based on detector data for a nearby link.

Rule 4: Traffic volumes were calculated based on the average detector results from more than one nearby link.

Rule 5: Traffic volumes were calculated based on an overall average proportional increase in traffic throughout the network.

A great deal of judgment was involved in the rules described above to update traffic volumes based on detectors measurements.

More general algorithms have been presented in the literature. Chin and Eager (40) examined techniques for

reducing the dimensionality of traffic flow in a network. They started with an existing set of detectors in the network and tried to reduce the number of detectors without adversely affecting the pattern matching scheme of the UTCS-1GC. Two models were presented in that study for the estimation of link volumes from detectorized approach measurements. The first model was a simple linear regression model that presented a relationship between the volume measurements on two links. The dependent variable in the model was the unknown volume and the independent variable was the known volume. The data used in model development were collected by a computerized traffic control system.

The second model presented in the study was a time series transfer function model based on the Box-Jenkins method. Comparing the two models indicated that either of the two may be employed to reduce the dimensionality of the flow vector with good reliability (40).

Okutani and Shimosato presented a multivariant regression model to estimate the nondetectorized link volume (41). In this model, the independent variables were the observed link volumes and the dependent variable was the unobserved link volume.

Later, Okutani (41) extended the above model to take time series of the traffic volume into account. This was done by adding to the regression equation independent

variables representing observed link volumes at time intervals preceding the time interval for which the volume estimation was needed. It was shown that the performance of the multiple linear regression model improved when link volume counts from up to seven preceding five-minute intervals were included as independent variables in the model.

In the same study (41), the Kalman filtering technique was employed to derive an estimation model of the nondetectorized link volume. The Kalman filtering algorithm is one of the most advanced methods in modern control theory. Volume estimations using the multiple linear regression and the Kalman filtering technique were compared using data from a small network. The results indicated that the Kalman filtering model produced better estimates compared to the regression model.

Balancing Traffic Counts

Partly because of counting errors and partly because counts may be carried out on different days, traffic counts on links of a network are unlikely to satisfy the flow conservation constraint, flow in equal to flow out, at every node and every approach in the network. The observed flows, thus, are considered to be internally inconsistent (42,43).

Sometimes balanced data are needed and the counts must be adjusted. However, a change in one count will affect many other counts throughout the network. Finding the right

combination of adjustments to make manually can be extremely difficult (44).

Van Zuylen and Willumsen (42) developed a model to estimate the most likely origin-destination matrix from traffic counts. For this purpose, the input flow to each node in the network had to be equal to the output flow from that node.

A statistically based model was developed in that study to balance a network of traffic counts. The model used a maximum likelihood method and assumed Poisson distributed single link counts.

A set of simultaneous equations for each constrained node (intersection) was constructed. Nodes representing traffic zones are unconstrained, since the volume entering does not have to equal the volume exiting during a given time period for traffic zones.

The flows going into and out of an intersection can be corrected by means of the following formula.

$$V_a = \hat{V}_a \left(1 + \sum_i \delta_{ai} M_i\right)^{-1} \qquad (2.3)$$

where

V_a = the corrected flow for link a,

$\hat{V}_a$ = the observed flow,

δ_{ai} = 1 for flow going into node i and -1 for flows out of node i, and

M_i = the Lagrange multiplier and has to be solved by substitution of equation (2.3) in

$$\sum_a V_a \, \delta_{ai} = 0 \qquad (2.4)$$

A computer program (44) was written to apply the algorithm described above. This program was written to help solve the problem of count inconsistency.

CHAPTER THREE
DEVELOPMENT OF A THRESHOLD SELECTION MODEL BASED ON ESTIMATED VARIATION

Introduction

The models developed in this study for determining the timing pattern change thresholds deal specifically with the traffic responsive strategy of the Transyt 3800 closed loop system. The normal pattern selection process of this strategy is based on arterial traffic volume level for cycle length selection, on directionality of flow for offset plan selection and on arterial traffic to side street traffic volume differential for split plan selection.

When the three signal timing parameters (the cycle length, the offsets and the splits) are selected in the TRSP mode, the conditions used in the selection of these parameters are analyzed independently in the master controller. Thus, transfer thresholds should be determined for each of the three parameters. As explained earlier, due to the limited detector information available from a typical closed loop system, the thresholds obtained are not globally optimal. However, the application of the models developed herein should improve the system operation by replacing the element of judgment by a more objective technique.

To obtain the transfer thresholds for a given timing parameter, it was necessary to identify the traffic conditions[5] at which each design of that parameter performed best compared to the other parameter designs. For this purpose, traffic flow conditions in the system were varied in a controlled manner. Then TRANSYT-7F was used to evaluate the performance of each design with the resultant traffic conditions.

Information about traffic flow conditions in a system is obtained from system sensors located on only a few approaches. Thus, the controlled variations in this study were only applied to the volume on the detectorized approaches. This meant that for each traffic condition investigated, only the volumes on the detectorized approaches were known. However, to evaluate these conditions using TRANSYT-7F, the value of flow on every link in the system is required. Thus, for each traffic condition resulting from varying the volumes on the system sensors, the turning movement volumes in the system had to be estimated.

This chapter presents the methodology used to obtain the transfer thresholds required for the normal operation of

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[5]In this dissertation a traffic condition is identified by the three traffic parameters used in the selection of the cycle, the offsets and the splits. These are the arterial volume level, the directionality of flow, and the arterial traffic to side street traffic volume differential, respectively.

the TRSP mode of the system. First the chapter addresses the data requirements. A method is then presented to calculate a reference volume for each link in the system. Next, the method used to vary the volume on the detectorized approaches to simulate different traffic conditions in the system is explained. The estimated variation model is then developed to estimate the nondetectorized volumes in the system. Finally, the method used to determine the transfer thresholds for the signal timing parameters is presented.

Data Requirements

The data required for the models developed in this study include information which should be available to the traffic engineering agency from data collected in the field.

TRANSYT-7F and PASSER-II[84] are used for the design and evaluation of signal timing parameters. Thus, the input data required for running these two programs had to be obtained. Five major types of data were required for this purpose: network data, traffic volume data, saturation flow data, speed data and signal timing data (8,9). The traffic volume data set used consisted of 15-minute turning movement counts for every approach at every intersection in the system.

The turning movement counts were utilized in various steps of the models developed in this study. They were used in the calculation of reference volumes for each link in the system. They were also used for estimating the traffic

condition variation during the day and for obtaining the correlations between the movements in the system.

Count data were also used to estimate the nondetectorized traffic volume in the estimated variation model. As will be explained later, the estimated variation model depends on reliable traffic volume data. Also, the model requires that count data should be obtained for as long a period as possible to reflect the variations in traffic conditions during the day.

Computer programs were written in this study using count data in various steps of the models. The count data were saved in a data set with a standard format for later use by these programs.

Reference Volume Calculation

In this study, a reference volume was determined for each link in the system. At any given traffic condition, the volume level on the link was represented as a proportion of that reference volume. The reference volume can be obtained as follows:

$$REFV_i = MEANV_i + 2 \cdot STDV_i \qquad (3.1)$$

where

$REFV_i$ = the reference volume on link i,

$MEANV_i$ = the mean of volume counts on link i, and

$STDV_i$ = the standard deviation of volume counts on link i.

Equation (3.1) was used for reference volume computations because this is fairly common in practice. If the counts are normally distributed, approximately 95% of them would be less than the reference volume. Traffic counts tend to deviate from a normal distribution, skewed toward low volumes, and consequently more than 95% may lie below the reference volume.

The estimated variation model used to obtain the non-detectorized link volume in this study requires the adjustment of the traffic counts to achieve a balance between input flows and output flows for each internal approach in the system. The adjustment procedure will be described later. The adjusted counts were used in reference volume calculations. In this manner, the same count data set was used in various steps of the model.

The reference volume of an approach is defined as the sum of the reference volumes of the turning movements downstream of that approach.

If a given link volume was computed to be below a minimum value, 100 veh/hr, the link reference volume was set to the minimum. The 100 veh/hr is the volume normally accommodated on the minimum green time. A computer program was written to calculate a reference volume for each link in the system.

<u>Simulating Different Traffic Conditions in the System</u>

In the normal operation of the TRSP mode, traffic conditions in the system are defined by system sensor measurements. The system uses three traffic volume parameters to define traffic conditions for the signal timing selection. These parameters are

1. The arterial volume level (AVL) is defined as the inbound or the outbound volume level, whichever is higher. (The volume level in a given direction is defined as the percentage of a reference volume programmed for that direction.)

2. The inbound-outbound volume differential (IOVD) is defined as the difference between the inbound and the outbound volume level.

3. The cross street arterial volume differential (CAVD) is defined as the difference between the cross street volume level and the arterial volume level.

This section describes the method used to simulate a given traffic condition in the system by changing the volume on the detectorized approaches in a controlled manner. The basic technique used was to multiply the reference volumes on the detectorized approaches by factors which were constant for a given direction. This technique is illustrated in Figure 3.1. Figure 3.1 (a) shows that a system with the volume on each detectorized approach was equal to the reference volume of that approach. In this case the AVL was

Figure 3.1. Simulating different traffic conditions in an arterial system.

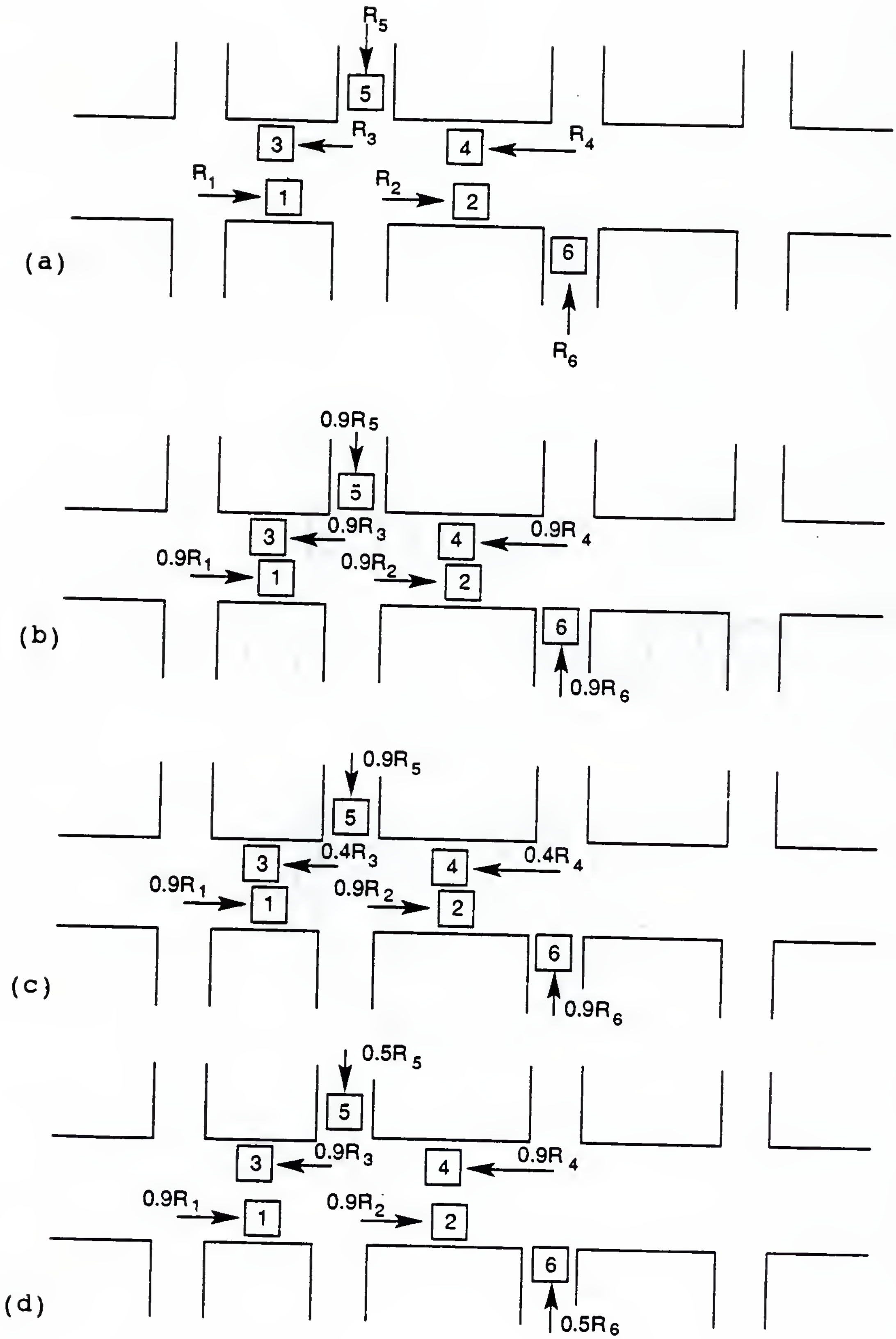
(a) An artery with 100% AVL, zero IOVD and zero CAVD.

(b) An artery with 90% AVL, zero IOVD and zero CAVD.

(c) An artery with 90% AVL, 50% IOVD and zero CAVD.

(d) An artery with 90% AVL, zero IOVD and -40% CAVD.

NOTE: R_i represents the reference volume for detectorized approach i.


(a)
R5
5
R3
3
R4
4
R1
1
R2
2
6
R6
(b)
0.9R5
0.9R3
0.9R4
0.9R1
0.9R2
0.9R6
(c)
0.9R5
0.4R3
0.4R4
0.9R1
0.9R2
0.9R6
(d)
0.5R5
0.9R3
0.9R4
0.9R1
0.9R2
0.5R6

100%, the IOVD was zero, and the CAVD was zero. By using appropriate multipliers, the AVL, the IOVD and the CAVD were changed to produce a required traffic condition as follows:

1. The AVL was changed by multiplying the reference volumes of the detectorized approaches on the artery by a constant factor. To keep the CAVD constant, the reference volumes of the cross street detectorized approaches were multiplied by the same factor. This is illustrated in Figure 3.1(b).

2. At a given AVL, the IOVD was changed by holding constant the volume in the direction required to be the heavy direction, while decreasing the volume on the other direction. In this process, the cross street detector volumes were kept constant. This is illustrated in Figure 3.1(c).

3. At a given level of AVL, the CAVD was varied by keeping the volume on the arterial detectors constant while changing the volumes on the cross street detectors by multiplying them by a constant factor. This is illustrated in Figure 3.1(d).

The method used to produce different traffic conditions in the system was in accordance with the closed loop system definitions of these conditions.

Estimated Variation Model

The threshold model developed in this study requires evaluation of the performance of each signal timing design

with different traffic conditions obtained as illustrated in the previous section. The TRANSYT-7F model was used for this purpose.

TRANSYT-7F needs the value of flow on every link in the system. In the closed loop system, traffic conditions are defined by the volume level on the detectorized approaches in each movement direction. The turning movement volumes in the network, therefore, had to be estimated based on the detectorized approach volumes. This section describes a model developed for this purpose. The model is referred to as the estimated variation model. First, the concept of this model is addressed, then the development of the model is presented.

Model Concept

Essentially, the purpose of the estimated variation model is to express the volume on each nondetectorized approach in the system as a linear function of volumes on detectorized approaches. Thus, when the volumes on the detectorized approaches were known, the volume on each non-detectorized approach could be estimated using these linear functions. The turning movement volumes on each approach were then calculated by assuming constant turning percentages in the system. Better results would be expected if an estimation equation was obtained for each turning movement volume in the system. However, more computations will be required in this case. In this study, it was decided to

simplify the calculations by assuming constant turning percentages in the system.

The linear functions were derived based on traffic count data. Before deriving these functions, however, an adjustment to the count data was needed. Ideally, for a given count period, input flows and output flows for each approach in the system should be equal, in order to obtain a good estimate for the volume on that approach. Normally, field data do not satisfy this idealization, partly because of counting errors and partly because counts may be carried out on different days.

A least squares adjustment model was derived to adjust the count data such that a balance between the input flow and the output flow for each internal approach in the system was obtained. The least squares principle ensured that any variation in the observations necessitated by the existence of inconsistencies with the model must be as small as possible taking into consideration the variable weights and subjected to the constrains of the problem (45,46).

In mathematical notation the least squares principle is

$$\text{Minimize } P = V^t W V \qquad (3.2)$$

where

V = the vector of the residuals which are equal to the adjusted variables minus the unadjusted variables,

W = the symetrical weight matrix of the vari ables, and

V^t = the transpose of the V vector.

The least squares adjustment model is a mathematical model. Michail and Ackermann (45) considered the model to be composed of two parts: the functional model and the stochastic model. The functional model describes the deterministic properties of the physical situation or event under consideration. A set of mathematical equations, referred to as condition equations, is written to describe the functional model of the adjustment problem. The stochastic model describes the nondeterministic properties of the variables. The derivation of the least squares adjustment model is presented in Appendix A.

After the adjustment, multiple linear regression analysis was used to derive equations which expressed the volumes on the nondetectorized approaches as linear functions of detectorized approach volumes. These equations were derived based on the adjusted count data.

Multiple linear regression permits the assessment of the relationship between one variable and another set of variables. The relationship is expressed as a linear equation that predicts a dependent variable from a function of independent variables (47,48).

A linear relationship between a nondetectorized approach volume (the dependent variable) and detectorized volumes (the independent variables) can be estimated and tested by estimating and testing the parameters in the model

$$NONDET_k = \beta_0 + \beta_1 \, DET_1 + \beta_2 \, DET_2 + \ldots + \beta_i \, DET_i + \ldots + \beta_n \, DET_n \tag{3.3}$$

where

$NONDET_k$ = the kth nondetectorized approach volume,

DET_i = the ith detectorized approach volume, and

β_i = the ith parameter of the model.

Appendix B illustrates how to estimate the parameters in a multiple linear regression model.

The estimated variation model assumes that good estimates of the nondetectorized approach volumes can be obtained from detectorized approach volumes. This depends on how well the detector locations have been selected and also on the degree of correlation between the volumes on system approaches. In fact, good correlations between movements in any given direction of travel (inbound, outbound and cross street) are an essential requirement for this type of traffic responsive system to be effective. The small number of

detectors installed in each direction is meant to represent the volumes on all approaches in that direction.

The model also needs good field count data. Adjusting unreliable data may adversely affect results with the model. The least squares adjustment model assumes that all counts are equally valid and will attempt to adjust all counts to incorporate incorrect values. Also, the use of unreliable data to derive estimation equations in regression analysis reduces the reliability of these equations.

For the estimation model to be efficient, count data should be obtained for a time period adequate to take into account as much traffic flow variation as possible during the day.

Model Development

Step 1: Count data adjustment

A least squares adjustment model was developed to obtain a balance between upstream input flows and downstream flows for each internal approach in the artery. The sums of the volumes in the system before and after the adjustment were assumed to remain constant during the adjustment process.

No turning movement contributes to both inbound and outbound movements. This means that adjustment of a volume in one direction does not affect the movement volumes in the other direction. Thus, the adjustment problem was divided

into two problems, one for each direction. This reduced the sizes of the matrices involved in the computations.

The following condition equations were written to represent the functional model of an east-west artery with n intersections, as shown in Figure 3.2. For the east direction, the equations were:

$$ET_i + NR_i + SL_i - ET_{i+1} - EL_{i+1} - ER_{i+1} = 0 \qquad (3.4)$$

For $i = 1$ to $i = n-1$

$$\sum_{i=1}^{n} ET_i + \sum_{i=1}^{n-1} SL_i + \sum_{i=1}^{n-1} NR_i + \sum_{i+1}^{n} EL_i$$

$$+ \sum_{i+1}^{n} ER_i = SUMEST \qquad (3.5)$$

where

n = the total number of intersections,

ET_i, EL_i, ER_i = the through, left turn, and right turn movement volumes, respectively, at intersection i in the east direction;

NR_i = the northbound right turn movement volume at intersection i,

SL_i = the southbound left turn movement volume at intersection i, and

SUMEST = the sum of all movement volumes included in the functional model for the east direction before adjustment.

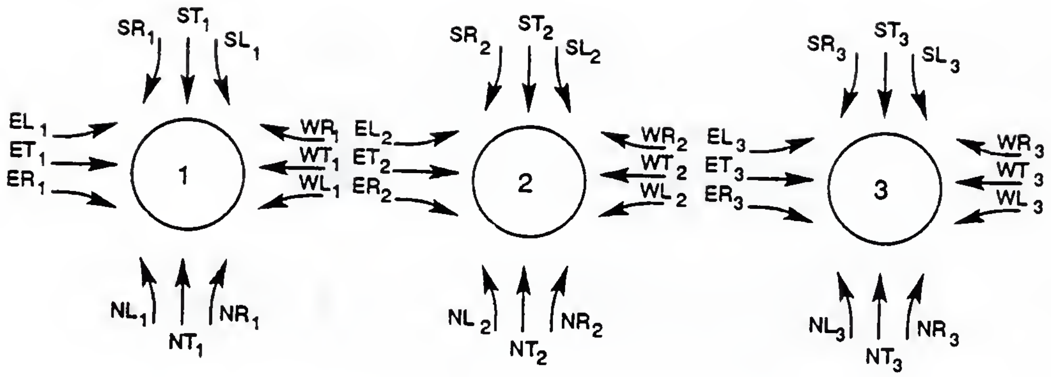


Figure 3.2. An east-west artery for which the turning movement volumes have to be adjusted.

For the west direction, the following equations were written.

$$WT_i + WL_i + WR_i - SR_{i+1} - NL_{i+1} - WT_{i+1} = 0 \qquad (3.6)$$

For i = 1 to i = n-1

$$\sum_{i=1}^{n} WT_i + \sum_{i=1}^{n-1} WL_i + \sum_{i=1}^{n-1} WR_i + \sum_{i=2}^{n} SR_i$$

$$+ \sum_{i=2}^{n} NL_i = SUMWST \qquad (3.7)$$

where

WT_i, WL_i, WR_i = the through, left turn, and right turn movement volumes, respectively, at intersection i in the west direction;

NL_i = the northbound left turn movement volume at intersection i,

SR_i = the southbound right turn movement volume at intersection i, and

SUMWST = the sum of all movement volume included in the functional model for the west direction before adjustment.

Flows from mid-block sources and sinks should be included as variables in the equations above.

The least squares adjustment model derived in Appendix A was used to find least squares estimates for all link volumes for each count period.

Before balancing the data, two inputs to the adjustment model had to be obtained. The first was the coefficient matrix, which included the coefficients of the functional model of the adjustment problem. This matrix was prepared manually.

The second input matrix required was the weight matrix. In the theory of adjustment, the term "weight" was used to express precision by way of an inverse relationship. Thus, high weight meant high precision which in turn meant a small standard deviation. A weight matrix should be obtained for movements in each direction on the artery. In this study, the inverse of the variance-covariance matrix obtained, based on the 15-minute historical count data, was used as the weight matrix. This matrix was obtained based on the count data using the Statistical Analysis System (SAS) (49). This concept will be treated in more detail in Chapter Six, in which an alternate method for obtaining the weight matrix will be suggested.

Since the least squares adjustment problem involved a sequence of matrix operations, the SAS interactive matrix language (SAS/IML) (50) was used for the adjustment model. The model adjusted the link volumes for a given time period

and for a particular movement direction. The adjustment was performed for every count period, for both directions.

Some turning movements in the system were not included in the least squares adjustment process described above. This was because those movements were neither input flows nor output flows for any of the system internal approaches. However, it was logical to modify these movements in order to take into consideration the adjustments made to other movements in the system. The unadjusted movements can be classified into two types:

1. Cross street movements were not included in the adjustment because they were not input flows to any internal approach. These included the cross street through movements on every intersection and also left and right turns from the cross streets on the first and last intersections. These movement volumes were adjusted by multiplying them by the coefficient C which is calculated as follows

$$C = \frac{SUMBEF}{SUMAFT} \tag{3.8}$$

where

C = a multiplier for cross street movements which had not been involved in the least squares adjustment,

SUMBEF = the sum, before the adjustment, of cross street turning movement volumes that were input flows to internal approaches, and

SUMAFT = the sum, after the adjustment, of cross street turning movement volumes that were input flows to internal approaches.

2. Right and left turns from the main street at the first and the last intersections were not included in the adjustment because they did not contribute to the output flow from any internal approach in the system. The volumes of these movements are adjusted by multiplying their values by the coefficient C_i, calculated as follows:

$$C_i = \frac{TBEF_i}{TAFT_i} \qquad (3.9)$$

where

C_i = a multiplier for approach i turning movement volumes which had not been involved in the adjustment,

$TBEF_i$ = the through volume downstream of approach i before the adjustment, and

$TAFT_i$ = the through volume downstream of approach i after the adjustment.

After the adjustment, the data for all time periods were appended to one file that had the same format as that of the data file before the adjustment. This enabled it to be used as input to the various computer programs developed in this study.

Example. As illustrated above, the least squares adjustment involves a sequence of matrix operations. The size of the matrices involved increased when more turning movements were involved in the adjustment. Thus, for the purpose of illustrating the computational technique of the model, it was necessary to use an artery with few turning movements as an example.

Three examples were used in developing the various concepts of this study. These examples are

1. A single bidirectional link in Gainesville, FL, used only to illustrate ideas which are computationally complex.

2. A six-link hypothetical artery with specified volume variations and specified relationships between individual movements. This was used to provide a high degree of control over the input data so that the relationship between cause and effect could be easily visualized.

3. A nine-intersection (16-link) artery in Lexington, KY. This was chosen as a practical example to demonstrate the determination of the thresholds using the estimated variation model and to compare the results with those obtained using the approximation (assumed variation) model. More trivial and hypothetical examples would not make a very convincing demonstration.

Of these examples, the first one was the most appropriate to illustrate the complex computation of the least

squares adjustment model. This is a two-intersection arterial system on 16th Avenue in Gainesville, FL. Figure 3.3(a) shows the turning movement volumes in the arterial system for a given time period.

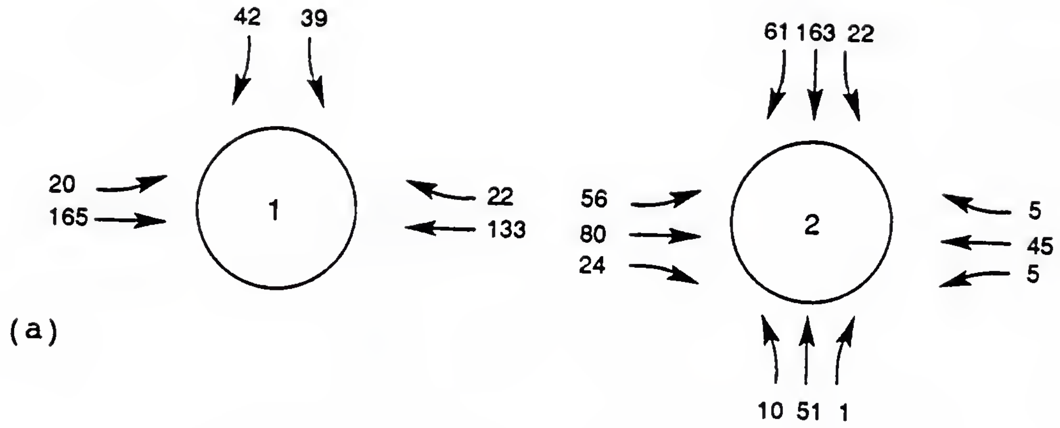
In this example, least squares adjustment was used to balance the upstream and downstream flows in the artery for this time period. As stated above, a SAS/IML program was written to perform the adjustment. The computations required for the adjustment are presented here for illustration purposes.

First the movement volumes in the east direction were adjusted. The following equations were written to represent the functional model of the adjustment problem in the east direction (SUMEST was calculated for this count period to be 364 vph)

$$ET_1 + SL_1 - EL_2 - ER_2 - ET_2 = 0 \quad . . . \quad (3.10)$$

$$ET_1 + SL_1 + EL_2 + ER_2 + ET_2 = 364 \quad . . . \quad (3.11)$$

Next, the least squares stochastic adjustment model derived in Appendix A was used to balance the flow in the system. From equations (3.10) and (3.11), the A matrix and the D vector were obtained as follows:



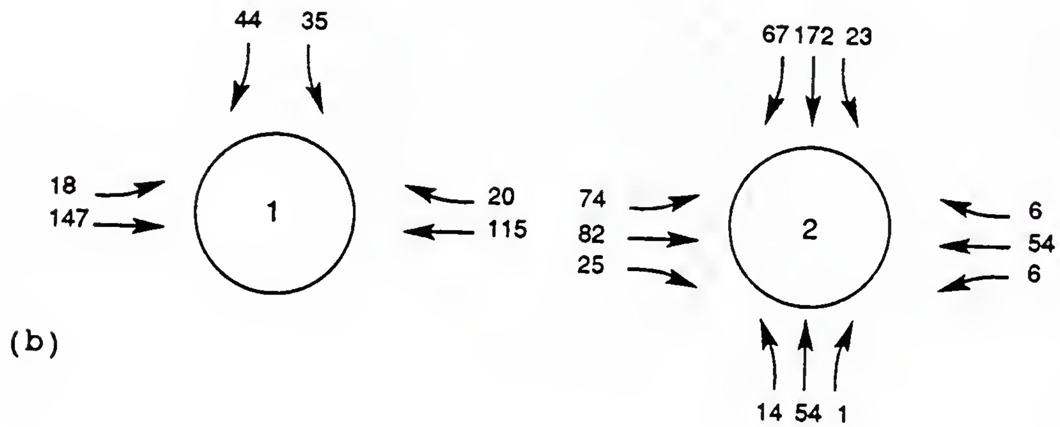


Figure 3.3. The adjustment of the turning movement volumes on a two-intersection arterial system in Gainesville, FL.

(a) The turning movement volumes in the arterial system before the adjustment.

(b) The turning movement volumes in the arterial system after the adjustment.

$$A = \begin{bmatrix} 1 & 1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 \\ 364 \end{bmatrix}$$

Vector F was calculated as

$$F = D - AL$$

$$= \begin{bmatrix} 0 \\ 364 \end{bmatrix} - \begin{bmatrix} 1 & 1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 165 \\ 39 \\ 56 \\ 24 \\ 80 \end{bmatrix}$$

$$= \begin{bmatrix} -44 \\ 0 \end{bmatrix}$$

In this example, the inverse of the variance-covariance matrix was used as the weight matrix. For the east direction, the variance-covariance matrix, Q, was obtained based on count data using SAS. Q, A, and A^t were substituted in the following equation to obtain the Q_e matrix.

$$Q_e = AQA^t$$

This resulted in

$$Q_e = \begin{bmatrix} 1 & 1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \cdot$$

$$\begin{bmatrix} 1098.0 & 226.0 & 254.6 & 123.1 & 633.0 \\ 226.0 & 70.7 & 45.9 & 36.1 & 145.4 \\ 254.6 & 45.9 & 202.1 & 40.6 & 173.4 \\ 123.1 & 36.1 & 40.6 & 31.3 & 79.5 \\ 633.0 & 154.4 & 173.4 & 79.5 & 445.7 \end{bmatrix} \cdot \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ -1 & 1 \\ -1 & 1 \\ -1 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 410.3 & 354.6 \\ 354.6 & 5363.3 \end{bmatrix}$$

$$Q_e^{-1} = \begin{bmatrix} 0.0026 & -0.0002 \\ -0.0002 & 0.0002 \end{bmatrix}$$

Next, the Lagrange multiplier, K, was calculated as follows:

$$K = Q_e^{-1} F$$

$$= \begin{bmatrix} 0.0026 & -0.0002 \\ -0.0002 & 0.0002 \end{bmatrix} \begin{bmatrix} -44 \\ 0 \end{bmatrix} = \begin{bmatrix} -0.114 \\ 0.0075 \end{bmatrix}$$

The vector of residuals V was calculated as follows:

$$V = Q\,A^t\,K$$

Substituting for Q, A^t, and K in the above equation and multiplying resulted in

$$V = \begin{bmatrix} -18 \\ -\ 4 \\ +18 \\ +\ 1 \\ +\ 2 \end{bmatrix}$$

The adjusted count data could then be calculated by adding the vector of residuals to the vector of unadjusted counts.

$$L = \begin{bmatrix} 165 \\ 39 \\ 56 \\ 24 \\ 80 \end{bmatrix} + \begin{bmatrix} -18 \\ -\ 4 \\ +18 \\ +\ 1 \\ +\ 2 \end{bmatrix} = \begin{bmatrix} 147 \\ 35 \\ 74 \\ 25 \\ 82 \end{bmatrix}$$

The vector of residuals was calculated for the movements in the west direction in a similar manner. The following vector was obtained

$$V = \begin{bmatrix} -18 \\ -\ 2 \\ +\ 6 \\ +\ 4 \\ +\ 9 \end{bmatrix}$$

and the adjusted counts in the west direction were calculated as follows:

$$L = \begin{bmatrix} 133 \\ 22 \\ 61 \\ 10 \\ 45 \end{bmatrix} + \begin{bmatrix} -18 \\ -\ 2 \\ +\ 6 \\ +\ 4 \\ +\ 9 \end{bmatrix} = \begin{bmatrix} 115 \\ 20 \\ 67 \\ 14 \\ 54 \end{bmatrix}$$

The movements that were not included in the least squares adjustment calculation presented above were adjusted using the coefficients C or C_i as described in the model formulation. The turning movement volumes in the system after the adjustment are shown in Figure 3.3(b).

A modification of the least squares adjustment method presented in this step is suggested in Chapter Six. In that modification, the weight matrix is calculated differently. To examine that modification, the solution of the problem presented in this example was repeated using the modified procedure. The results are presented in Appendix C.

Step 2: Development of volume estimation model structure

Multiple linear regression was used to derive estimation equations for volumes on the nondetectorized approaches (the dependent variables) from detector measurements (the independent variables). The regression was based on count data, adjusted as described previously. Approach volumes

were obtained from count data by summing the turning movements on the approach downstream.

Before performing the regression analysis, the correlation matrix between the volumes on the approaches with system sensors (the independent variables in the regression) was obtained using SAS. When some of the independent variables are highly intercorrelated, the computed estimates of the regression coefficients are unstable and their interpolation becomes tenuous (47). This problem is referred to as multicollinearity.

To solve this problem, if the examination of the correlation matrix obtained above indicates that two independent variables are highly correlated, then only one of the two is kept for use in the regression. This is a good way to handle the problem since one of the two variables conveys essentially all of the information contained in the other.

The second stage in solving the problem of multicollinearity involves the use of a variable selection process such as stepwise regression in SAS (51), to select the set of independent variables that best predicts a given dependent variable from the entire set of possible independent variables.

The third stage involves examining the correlation coefficient (R^2). This is a measure that indicates the portion of the total variation that is attributed to the fit rather than left to the residual error. This value is

presented in stepwise procedure output whenever an additional variable is selected. The independent variables that explain little of the variance in the dependent variable should be excluded.

The variable selection process explained above implicitly overcomes the multicollinearity problem. Small numbers, possibly one or two, of independent variables are preferred in the estimation equation.

One assumption of linear regression is homoscedasticity or the homogeneity of variance assumption. This assumption requires that the variance of the dependent variable at a given value of an independent variable be the same for all values of the independent variable. However, the count data can be assumed to be Poisson distributed. Thus, their variance is a function of their mean. This means that the variance depends on the independent variable values, which violates the homogeneity of variance assumption. A square root transformation of the dependent variable is used with Poisson distributed variables to solve this problem (47), and was used in this study. The linear regression was thus performed on the transformed values. A SAS program which utilizes the SAS REG procedure (51) was used to perform the regression analysis.

Example. A hypothetical route was used to illustrate the derivation of the estimation equations. This same example will be used in the remaining sections of this

chapter to illustrate the application of the estimated variation model and the method used to determine the thresholds. A simple hypothetical route was chosen as an example because of the complexity of the models. By applying the techniques to a relatively trivial case, the results may be visualized more readily.

As illustrated in Figure 3.4, the hypothetical artery is an east-west artery with four intersections. The signal phase sequence, the distance between intersections, and the detector locations are also shown in Figure 3.4. The three detector locations were selected such that there was one detector in each direction (inbound, outbound and cross street). As described in the data requirement section, 15-minute counts, for long enough periods, were needed on every link in the system to obtain the transfer thresholds. Therefore, in this example, 15-minute counts were fabricated for a 12-hour period. The following method was used for this purpose:

1. Hypothetical 15-minute counts on the detectorized approaches were fabricated to represent variations in the AVL, CAVD, and IOVD during the 12-hour period.

2. The counts on the nondetectorized approaches were fabricated such that they had good correlation with the counts on the detectorized approach in the same direction. This correlation was necessary for the TRSP selection of

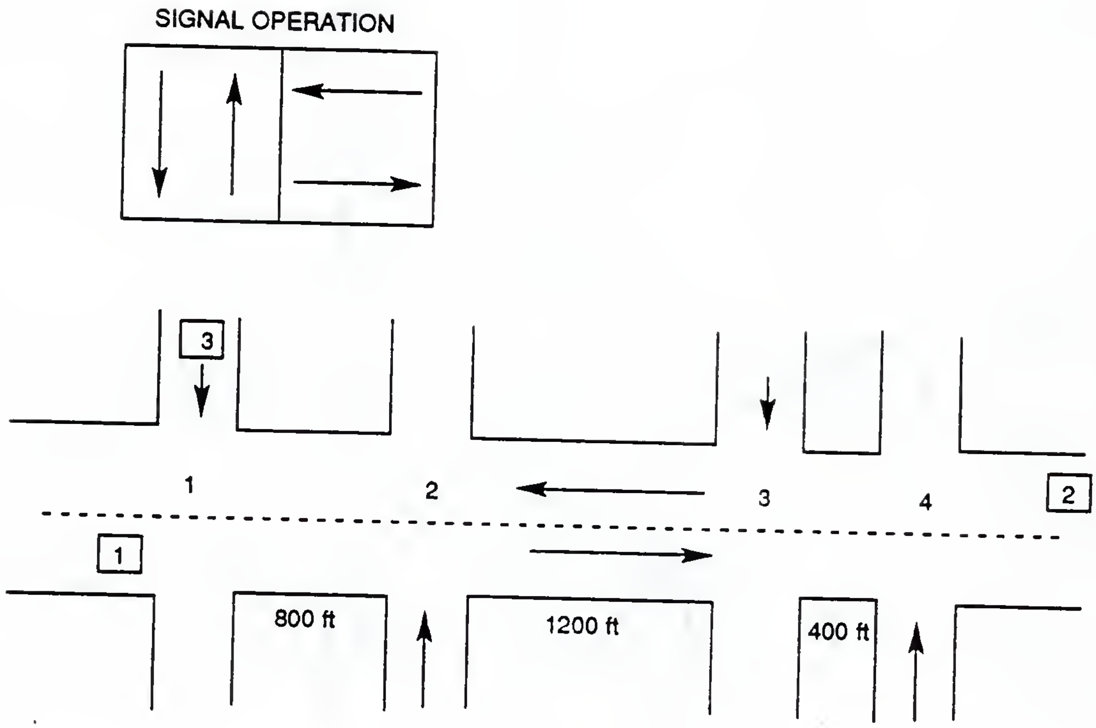


Figure 3.4. The hypothetical artery layout, phase sequences, and system sensor locations.

cycle, offsets, and splits to be effective. The following formula was used.

$$VU_i = VD_i \quad (1 + CV \bullet R_n) \qquad (3.12)$$

where

VU_i = the volume on the nondetectorized approach in the ith direction,

VD_i = the volume on the detectorized approach in the ith direction,

CV = the variation of volume on the non-detectorized approach compared to the volume on the detectorized approach, and

R_n = a standard normal random variable generated using the Box-Muller method.

In the above formula, for each count period, a random error component was added to the volume of the detectorized approach to represent the volume on a nondetectorized approach in the same direction. In this manner, the required correlation was obtained. The magnitude of this correlation could be controlled by the value of the coefficient of variation CV in equation (3.12). In this example, it was assumed that the correlations between the cross street movements were less than the correlation between the inbound movements or the outbound movements. Thus, the CV values used were 0.15 and 0.175 for the arterial and the cross

street movements, respectively. A program written in SAS was used to generate the counts as explained above.

A multiple linear regression analysis was performed on the hypothetical data to derive estimation equations for the nondetectorized approach volumes. Table 3.1 shows the result of the regression analyses. As shown in the table, the R^2 values were between 0.74 and 0.84 for the cross street movements and between 0.84 and 0.89 for the arterial movements.

Step 3: Application of the estimated variation model

As explained earlier, examination of signal timing parameter designs, under different traffic conditions, requires the estimation of the nondetectorized link volumes. This estimation was performed for each traffic condition determined as described in the previous section.

First the estimation equations, derived in step 2, were used to estimate the nondetectorized approach volumes from detectorized approach volumes. Then, assuming that the turning percentages at the intersections were constants, the turning movement volumes from each approach could be determined. The turning percentages for a given approach were obtained based on the reference volumes of the turning movements downstream of the approach.

A computer program was developed for this study to calculate the turning movement volumes in the system based on the regression parameters of the estimation equations,

Table 3.1 The Estimation Equations for the Nondetectorized Approach Volumes on the Four-Intersection Hypothetical Artery

Inter-section	Approach	Equation Coefficients[a] β_0	β_1	β_2	β_3	R^2
1	East	D[b]	D[b]	D[b]	D[b]	-
	West	5.346	0	0.045	0	0.89
	South	D[b]	D[b]	D[b]	D[b]	-
2	East	5.501	0.045	0	0	0.88
	West	6.571	0	0.035	0	0.83
	North	4.07	0	0	0.06	0.74
3	East	6.020	0.038	0	0	0.88
	West	5.841	0	0.0431	0	0.89
	South	4.271	0	0	0.057	0.80
4	East	5.849	0.0401	0	0	0.83
	West	D[b]	D[b]	D[b]	D[b]	-
	North	2.987	0	0	0.073	0.84

[a] Equation form: $(\mathrm{UNDET}_k)^{1/2} = \beta_o + \beta_1\ \mathrm{DET}_1 + \beta_2\ \mathrm{DET}_2 + \beta_2\ \mathrm{DET}_3$

[b] D indicates that this approach is detectorized.

the turning movement percentages for each approach, and the detector volumes.

The Arterial Analysis Package (AAP) (52) was used for coding the data. The AAP data files were then converted to TRANSYT-7F or PASSER-II input data files as required.

To reduce the effort required to code the data for each volume condition, a program was written to modify the AAP input deck such that the coded volume was changed as required to eliminate the manual coding each time a new volume condition was investigated.

Example. The four-intersection hypothetical artery of Figure 3.4 was used to illustrate the nondetectorized volume estimation. Figure 3.5(a) shows the system with each detectorized approach volume equal to the reference volume of that approach. Figure 3.5(b) shows the volume on these approaches for a specific volume condition, determined as explained earlier in this chapter. The volumes on the nondetectorized approaches were calculated using the equations presented in Table 3.1 and are shown in Figure 3.5(c).

Threshold Determination

Method Concept

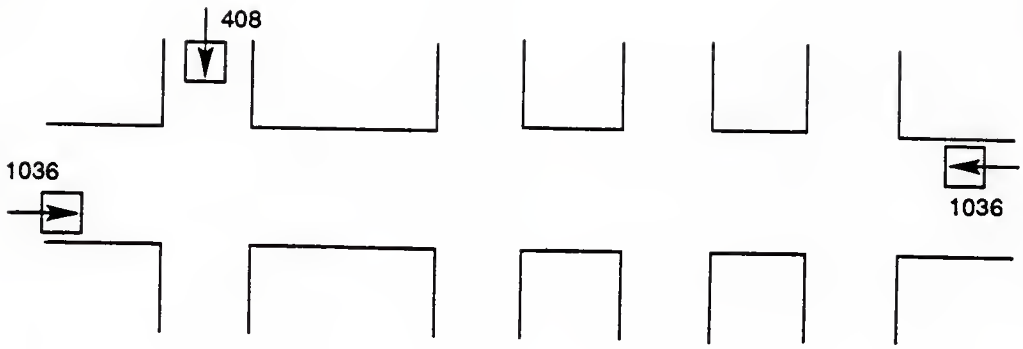
This section describes the method used to determine transfer thresholds for the signal timing parameters. To determine these thresholds for the cycle lengths, the offsets and the splits, TRANSYT-7F input files with different AVL, CAVD and IOVD, respectively, had to be created. These

Figure 3.5. The estimation of the nondetectorized volumes in the four-intersection hypothetical artery using the estimated variation model.

(a) The artery with the volume on all detectorized approaches equal to their reference volume (AVL = 100%, CAVD = zero and IOVD = zero).

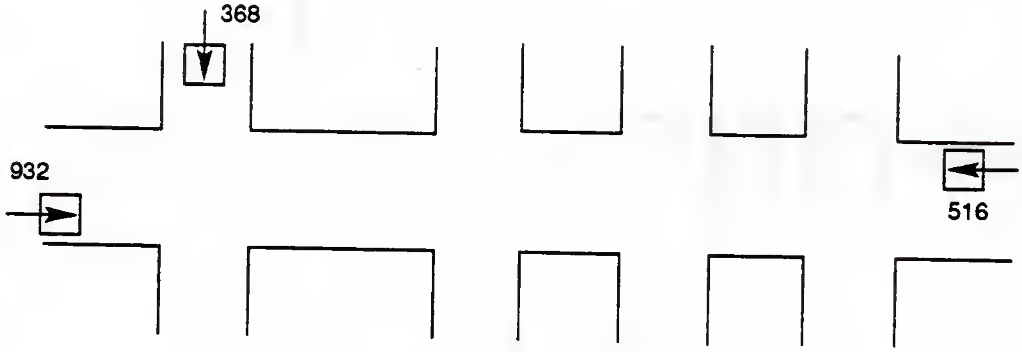
(b) The artery with the traffic condition to be investigated (AVL = 90%, CAVD = zero and IOVD = 40%).

(c) The turning movement volumes in the system estimated using the estimated variation model.



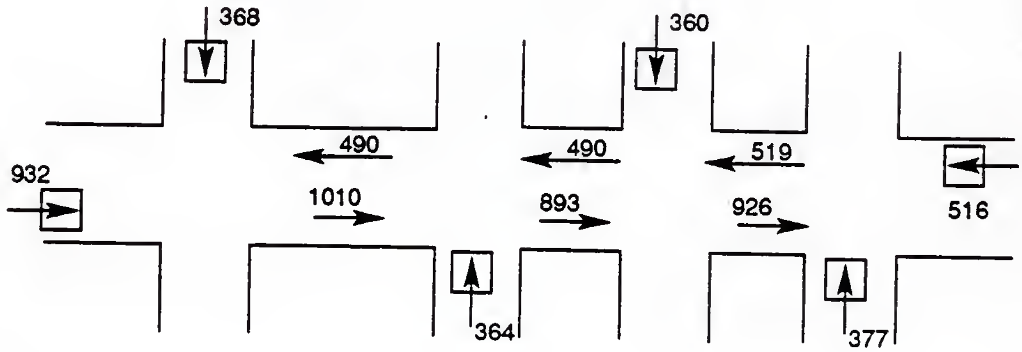
408
1036
1036

(a)



368
932
516

(b)



368
360
490
490
519
932
1010
893
926
516
364
377

(c)

files were produced using the method explained in the previous sections of this chapter. They were used in the evaluation of different parameter designs under different traffic conditions. A design was selected for implementation for a given traffic condition, if it produced the lowest TRANSYT-7F performance index compared to the other designs of that parameter.

In the TRSP operation investigated, the system can be programmed to implement the TRSP selections of the cycle, the offsets and the splits. The conditions used in selecting these parameters are analyzed independently in the master controller. Thus, transfer thresholds should be determined for each of the three parameters. This is one of the limitations of this type of TRSP selection. Ideally, the signal timing parameters should be optimized simultaneously to obtain the best performance of the system.

The TRSP selection of split plans can be disabled by the system engineer at some or all of the intersections. In this case, the system supervisors at the local intersections are programmed to select the split plan based on a combination of cycle and offset in effect. If this is the case, one of 12 different split plans can be selected for each cycle and offset combination. As will be described later, disabling the TRSP selection of splits affected the method used to determine the transfer thresholds.

Examining the TRSP operation described above suggests that there are two situations where the disabling of the TRSP selection of splits is preferred. The first is when the cross street movements at an intersection are not correlated with the cross street detectorized approaches. In this case, no benefit is expected from implementing a TRSP selection of split plans at that intersection since the shift in the cross street detectorized volume does not represent a shift in the cross street volumes at that intersection. The second situation is when the left turns from the main street are more critical than the cross street movements at an intersection. In the TRSP selection of the splits, the splits are chosen based on the CAVD independent of the IOVD. This seems inadequate when the left turns on the main street are heavy since these turns are normally related to the IOVD value. It might be better in this situation to relate the splits to the cycle and offsets in effect rather than using the TRSP selection of splits. This is especially true if the cross street movements are not heavy or if the CAVD do not vary a lot during the day.

Currently, the same split and offset thresholds are programmed independent of the cycle length in the master controller. Since the cycle length is selected based on the AVL, this means also that the same offset and split thresholds are used for all AVL. This might be another limitation of the TRSP operation investigated, since the best set

of offset and split thresholds might be different for different cycles. In this study, offset and split thresholds were calculated for each of the design cycles. The results were then compared to determine the effect of changing the cycle length on the threshold values.

The purpose of the model presented below is to determine switching thresholds for the signal timing plan parameters. The method used in this study for designing these parameters is not claimed to be the optimum. However, it represents a simple procedure for obtaining a good timing plan library that takes into consideration the expected variations in traffic conditions during the day.

<u>Method Development</u>

This section presents the steps required to determine the transfer thresholds for the timing plan parameters. The hypothetical artery, presented in Figure 3.4 was used to illustrate the procedure described in each step.

<u>Step 1: Determination of the design cycle lengths</u>

In the normal TRSP operation of the system, the master controller selects one of four design cycle lengths, based on the AVL in the system. The selection varies with demand, with heavier arterial volumes resulting in longer cycle lengths.

To select the design cycle, the lowest and the highest cycle lengths to be investigated were first determined. The lowest cycle length was chosen to be the minimum cycle that

satisfied the sum of minimum green times. The highest cycle length was obtained by choosing the smaller of the following two values.

1. The best cycle length determined by TRANSYT when the volume on each link in the system was equal to the link reference volume.

2. The maximum cycle that was accepted by the local traffic agency.

Then, as many cycles as possible, between the lowest and the highest cycle lengths, were tested to determine the four design cycles. The interval between the cycle lengths tested was constant and a multiple of five seconds.

As will be explained in the next step, the performances of these cycles under different traffic conditions in the system were determined. Then, based on these performances, the four design cycles were selected.

Example. For the hypothetical artery, the lowest cycle length that satisfied the sum of the minimum greens was 50 seconds. A TRANSYT-7F input file was created for the system with 100% AVL, zero CAVD, and zero IOVD. This represented a traffic condition in which the volume on every detectorized approach in the system was equal to the approach reference volume. The best cycle length for this condition was determined by TRANSYT-7F to be 150 seconds. Thus, this was chosen to be the highest cycle length included in the investigation.

Only five cycles between the lowest and the highest cycle lengths were selected for investigation in this hypothetical example. In practical designs, however, as many cycles as possible should be tested. The cycle lengths selected for investigation were 50, 75, 100, 125 and 150 seconds.

Step 2: Determination of cycle switching thresholds

TRANSYT-7F input files were created for the system with different AVL, zero CAVD, and zero IOVD. With each of these conditions, the signal timings were optimized using TRANSYT-7F for each of the cycle lengths chosen in Step 1. For a given traffic condition, a cycle was selected for implementation if it produced the lowest PI compared to the other cycles investigated. By examining the performances of these cycles, at different AVLs, the four cycles that performed the best were kept for use as the design cycles.

After the selection of the four design cycle lengths, the transfer thresholds were determined. This was done, again based on the performances of the design cycles at different AVLs, determined as explained above. Whenever a change in the AVL caused a new cycle to be selected, a logarithmic interpolation was performed between the two AVLs before and after the change to obtain the switching threshold to the new selected cycle. The logarithmic rather than the linear interpolation was used because the PI increases exponentially with the increase in the volume level.

A computer program was written to perform the required interpolation. The program also took into consideration the two special cases described below.

1. The cycle length maintained a monotonic relationship with the AVL. Thus, when arterial flow was increased, for example, the program did not permit switching back to a shorter cycle length which had been selected for a lower volume level.

2. Sometimes the change increment in the AVL resulted in selecting a new cycle other than the next higher or lower cycle to the one that had been selected before the change. This resulted in skipping design cycles. When this situation occurred, the volume range between the two AVLs before and after the change was divided into n+1 intervals of the same size, where n was the number of cycles between the old cycle and the new cycle. The thresholds were then chosen to be the boundaries that separated these intervals.

The treatment of the two special cases described above was meant to take into account the method used by the system to select the cycles.

<u>Example</u>. The performances of the five cycle lengths, selected for the four-intersection artery in the previous step, were tested at different AVLs. The results, presented in Table 3.2, indicated that the 100 second cycle was not selected at any volume level investigated. Thus, this cycle was excluded and the other four cycle lengths (50, 75, 125,

Table 3.2 The Effect of Changing the Cycle Length on the PI of the Hypothetical Artery Determined Using the Estimated Variation Model

AVL (%)	TRANSYT PI (Cycle)				
	50 Sec	75 Sec	100 Sec	125 Sec	150 Sec
60	<u>27.1</u>	28.4	27.7	28.0	29.1
70	36.2	<u>35.4</u>	35.7	35.8	36.9
80	49.9	49.6	48.2	<u>47.2</u>	48.4
90	100.8	76.4	70.3	70.1	<u>69.6</u>
100	372.2	229.4	182.1	159.4	<u>147.7</u>

NOTE: Underlining indicates that the cycle length which produced that PI should be selected for this AVL.

and 150 seconds) were used as the design cycles. As expected, as the AVL increased the selected cycle length also increased. The transfer thresholds obtained using the logarithmic interpolation are presented in Table 3.3.

Step 3: Design of offset plans

For each design cycle, different offset plans were computed to provide for the variations in the inbound-outbound differential conditions during the day.

TRANSYT-7F was used to design an offset plan for each of the three IOVD conditions. These IOVDs represented average, heavy inbound and heavy outbound volume conditions. To prepare offset plans for the three design conditions, the variable $ULAVL_i$ was defined to be the upper limit of the AVL interval for which the design cycle i was selected for implementation (as described in the previous step). Then, three offset design conditions for cycle i were determined from a system with AVL equal to $ULAVL_i$ and CAVD equal to zero by varying the IOVD.

TRANSYT-7F input files were created for these conditions using the estimated variation model. The method used in the design of the offset plans was different depending on whether the TRSP selection of splits was disabled or not at some or all intersections.

If the TRSP selection of split plans was allowed, then the three offset plans were designed for the same split plan because in this case the split plan selection was

Table 3.3 The Cycle Transfer Thresholds Determined Using the Estimated Variation Model for the Hypothetical Artery

Shorter Cycle (Sec)	Longer Cycle (Sec)	AVL to Transfer (%)
50	75	66
75	125	72
125	150	87

independent of the offset plan in effect. First, the offsets and the splits were optimized for the average condition (zero IOVD). Then, the resultant split plan was used as input to the other two offset optimization runs in which the splits were kept constant.

However, if the TRSP selection of split plans was disabled at some or all intersections, the splits for these intersections were decided by the offset plan in effect. In this case, both splits and offsets were optimized for these intersections when designing the three offset plans.

The feasibility of using TRANSYT-7F to determine the transfer thresholds for offset plans, designed using PASSER-II, was also investigated in this study. Five offset plans were designed for each cycle, using PASSER-II[84], by allocating five different minimum percentages of the total bandwidth to a given direction of travel along the artery. These offset plans represented heavy inbound, moderate inbound, average, moderate outbound and heavy outbound. The input volume to PASSER-II was the upper limit arterial volume level of the cycle ($ULAVL_i$).

<u>Example</u>. For the four intersections hypothesized, the cross street movements were highly correlated with each other and there were no left turns on the artery to affect the signal timing splits. Thus, the TRSP split plan selection was allowed for all the intersections in the system. TRANSYT-7F was used to design three offset plans for each of

three design cycle lengths to illustrate the method. These cycle lengths were 75, 125 and 150 seconds. PASSER-II[84] was also used to design five offset plans for the 125-second cycle.

Step 4: Determination of offset plan switching thresholds

For each cycle, TRANSYT-7F simulation runs were used to evaluate the effectiveness of the design offset plans under different inbound-outbound flow conditions. Both TRANSYT-7F and PASSER-II designs were evaluated. The conditions were determined for a given cycle i from a system with AVL equal to $ULAVL_i$ and CAVD equal zero by varying the IOVD. The IOVD conditions investigated ranged from heavy inbound to heavy outbound volumes. The estimated variation model was used to produce TRANSYT-7F input files for these conditions.

For a given cycle length and a particular inbound-outbound condition, a design offset plan was selected if it produced the minimum PI among the design offset plans for the cycle. When the controlled change in IOVD resulted in a change in the selected offset plan, an interpolation procedure was used to obtain the threshold to transfer from the old to the new selected offset plan. This interpolation was similar to that utilized in the cycle threshold determination with the exception that the interpolation was linear rather than logarithmic.

After the thresholds were determined for both TRANSYT-7F and PASSER-II designs, the results were analyzed to

determine if both methods produced good results. The TRANSYT-7F flow profile diagram (FPD), the time space diagram (TSD), the platoon progression diagram (PPD), and TRANSYT-7F measures of effectiveness (MOEs) were used in this analysis. Since the bandwidths are not direct outputs from TRANSYT-7F, the Progression Graphic and Optimization Program (PROGO) (53) was used to determine the bandwidths from TRANSYT-7F PPD files.

Example. To illustrate the procedure described in this step, the four-intersection hypothetical artery was used again. First, the possibility of determining transfer thresholds between the offset plans, designed using PASSER-II, was investigated. The results, presented in Table 3.4, indicated that the moderate inbound, the balanced and the moderate outbound designs were not selected under any inbound-outbound volume conditions. Only the heavy inbound and the heavy outbound designs were selected. The switching threshold between these two designs was close to zero IOVD.

In addition, Table 3.4 indicates that even if the volumes were significantly unbalanced the progression in the direction of the light movement produced better performance than the balanced PASSER-II design. The above result, which might seem surprising, could be explained based on Figures 3.6 to 3.8. These figures show the PPD's for the artery with heavy inbound volume when different PASSER-II designs were used. As expected, the progression in the heavier

Table 3.4 The Effect of Changing the Offset Plans, Designed Using PASSER-II on the Performance of the Hypothetical Artery for the 125-Second Cycle

IOVD (%)	TRANSYT PI (Design) Heavy Outbound	Moderate Outbound	Balanced	Moderate Inbound	Heavy Inbound
-50	<u>44.0</u>	48.6	56.5	52.1	51.6
-25	<u>49.9</u>	54.7	63.2	56.3	54.7
0	<u>62.7</u>	68.1	79.2	70.2	63.8
25	55.3	58.1	66.0	58.9	<u>52.4</u>
50	52.8	54.4	59.7	53.2	<u>46.5</u>

NOTE: Underlining indicates that the offset plan which produced that PI should be selected for this IOVD.

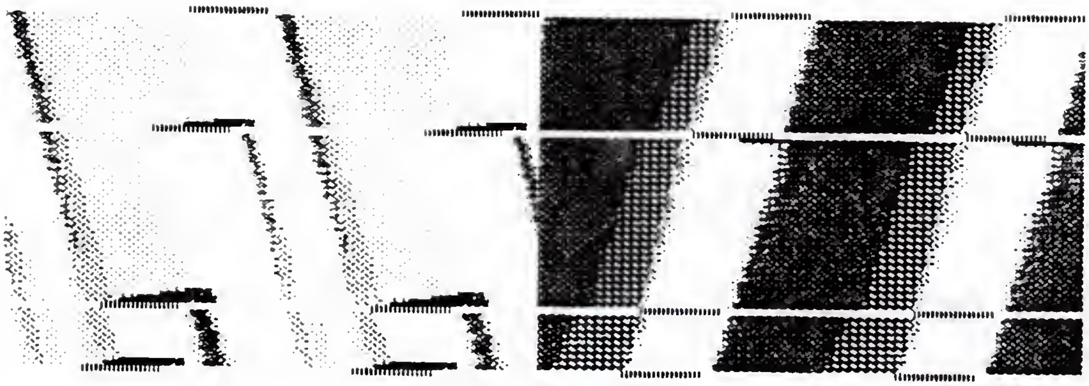


Figure 3.6. The Platoon Progression Diagram for the hypothetical artery with the heavy inbound volume under a heavy inbound progression design and 125-second cycle.

NOTE: The TSD orientation downbound on the page is outbound.

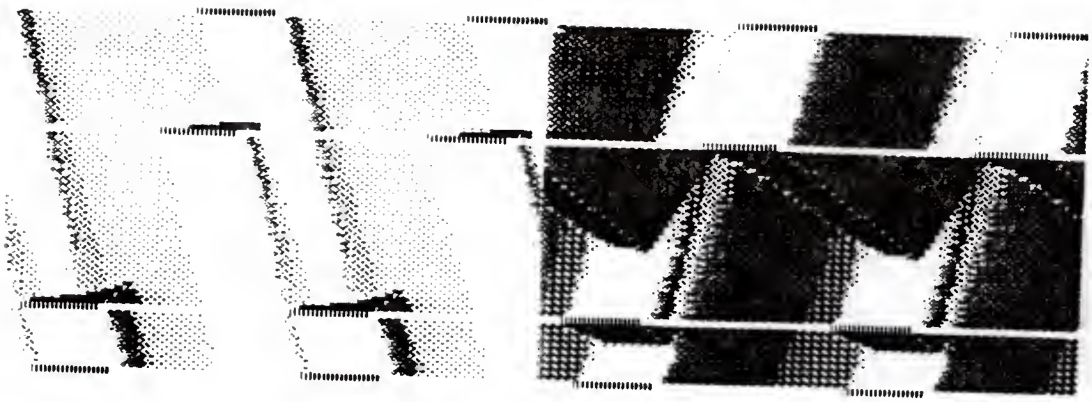


Figure 3.7. The Platoon Progression Diagram for the hypothetical artery with heavy inbound volume under a balanced progression design and 125-second cycle.

NOTE: The TSD orientation downbound on the page is outbound.

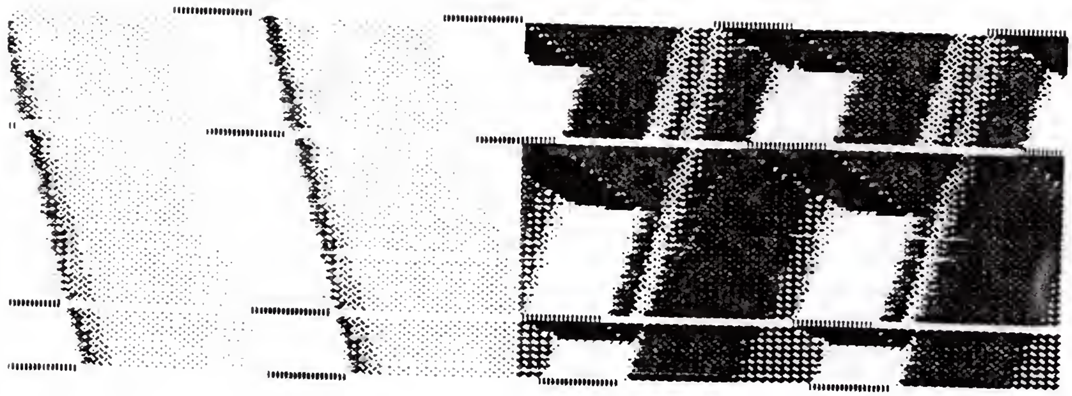


Figure 3.8. The Platoon Progression Diagram for the hypothetical artery with heavy inbound volume under a heavy outbound progression design and 125-second cycle.

NOTE: The TSD orientation downbound on the page is outbound.

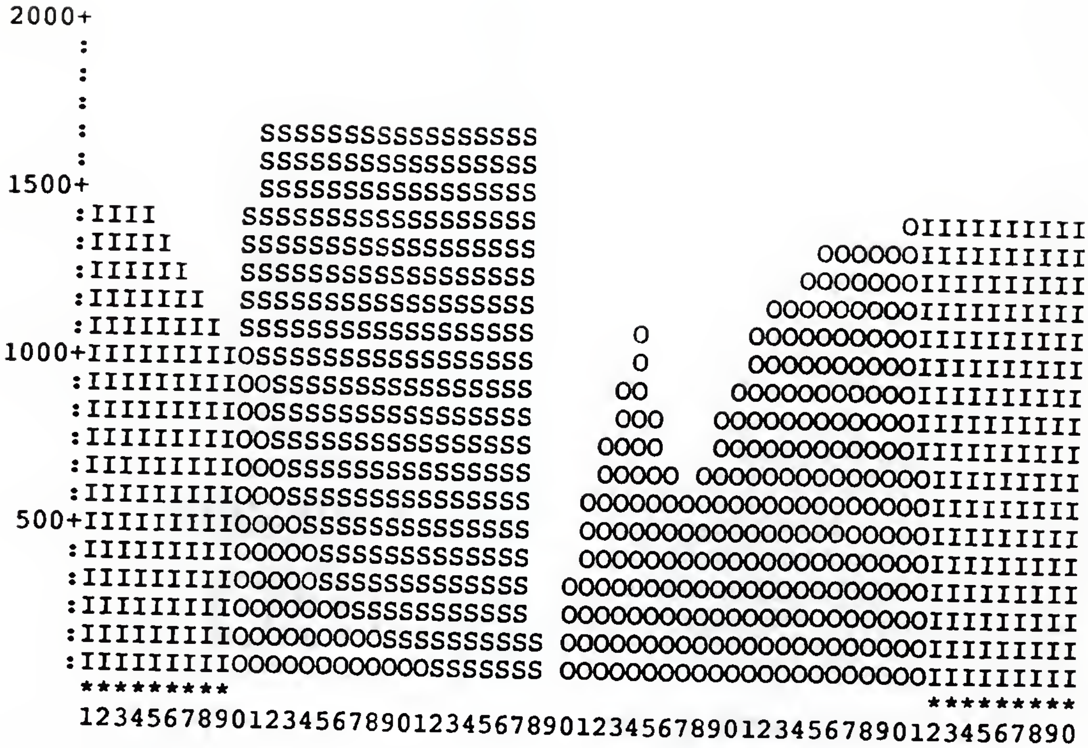
direction produced the best results. However, comparing the PPD diagrams for the balanced design with those for the lighter direction progression design illustrated why the balanced design had the higher PI. Although a larger proportion of the bandwidth would be available for the heavier direction in the case of balanced design, most vehicles arriving on green at the heavy approach to the second intersection joined the back of the queue that had been formed during the red period. A lesser proportion joined the back of the queue when the lighter direction progression was used. A comparison of the flow profile diagrams for the two conditions is presented in Figure 3.9. This comparison shows that when the progression in the lighter direction was implemented, the platoon of vehicles arrived at later stages of the green period after the queue had dissipated. Thus, fewer stops and shorter delays would result when applying this design compared to the balanced design.

To compare PASSER-II and TRANSYT-7F designs further, Figure 3.10 presents the PPDs for a two-intersection artery under a balanced PASSER-II design and a balanced TRANSYT-7F design. The artery was 1000 feet long with a 60-second cycle and undersaturated volume conditions. The volumes on the artery were balanced, with no turning movements from the cross streets. Although PASSER-II gave more bandwidth to each direction (24 seconds) compared to TRANSYT-7F which gave only 18 seconds to each direction, the TRANSYT-7F,

Figure 3.9. The Flow Profile Diagrams of the inbound approach to the second intersection under two PASSER-II designs.

(a) A heavy outbound progression design.

(b) A balanced design.


2000+
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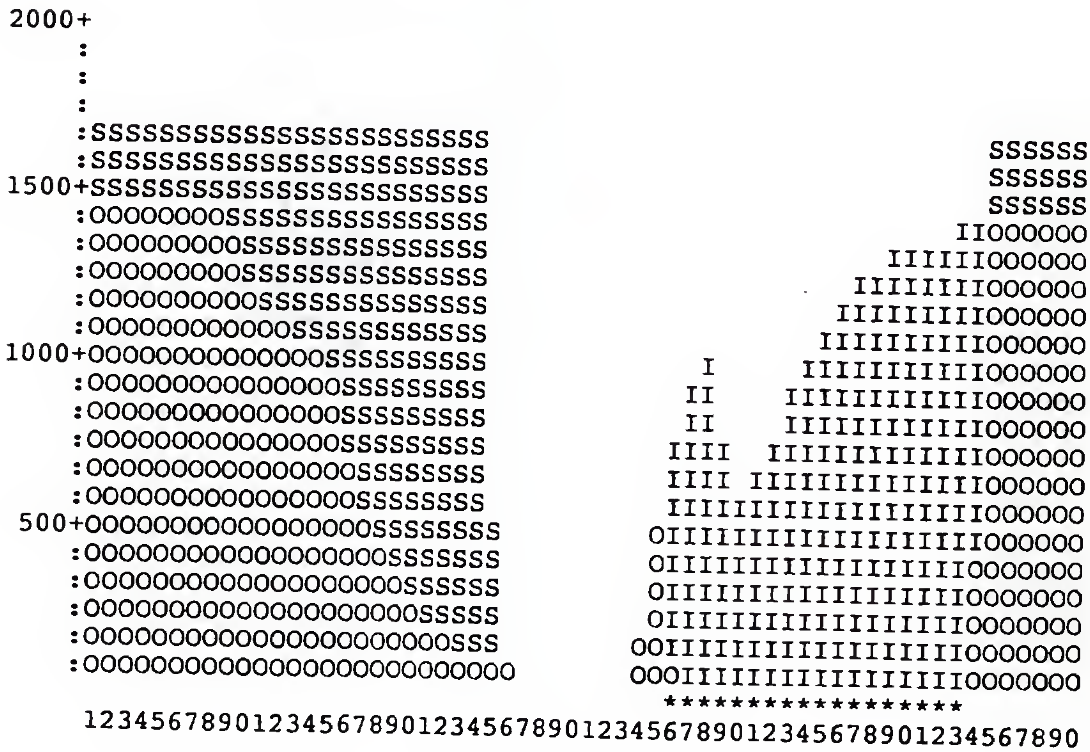
(a)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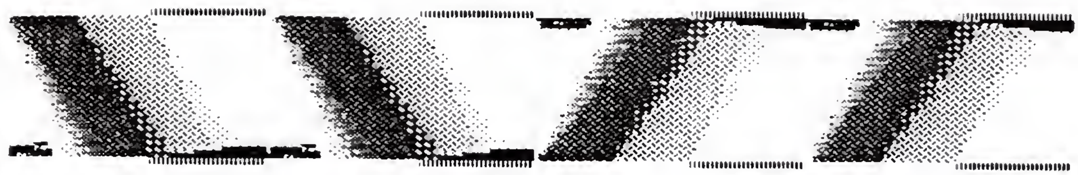
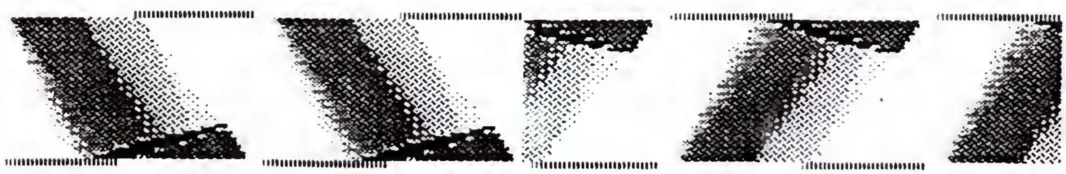
(b)



(a)



(b)

Figure 3.10. The Platoon Progression Diagrams for a two-intersection artery with balanced volume and under-saturated conditions under TRANSYT-7F and PASSER-II designs.

(a) TRANSYT-7F design.

(b) PASSER-II design.

NOTE: The TSD orientation downbound on the page is outbound.

design produced a lower PI (the PIs were 25.8 and 30.0 for TRANSYT-7F and PASSER-II designs, respectively). The reason for this was that in the case of a PASSER-II design, the platoon arrived downstream on steps of the cycle such that it joined the back of the queue.

PASSER-II and TRANSYT-7F employ different strategies. PASSER-II tries to maximize the bandwidth efficiency while the TRANSYT-7F evaluation is based on a disutility function consisting of a weighted sum of stops and delays. As described above, a better maximal bandwidth solution might not result in a better design from the TRANSYT-7F point of view. Thus, evaluation of the PASSER-II offset design by TRANSYT-7F to obtain the transfer threshold was not possible. For this reason, it was decided to use TRANSYT-7F to design the offset plans for the purpose of this study. Three offset plans were designed for heavy outbound, balanced, and heavy inbound volume conditions.

Table 3.5 illustrates the effect of varying the offset plans, designed by TRANSYT-7F, on the PI of the hypothetical artery for three cycle lengths. The offset transfer thresholds obtained are presented in Table 3.6. These thresholds were different for different cycle lengths. One of the important considerations in this respect was the TRANSYT-7F design of the offset for the zero IOVD (the balanced condition). Because TRANSYT-7F was concerned only with minimizing stops and delays and not distributing them

Table 3.5 The Effect of Changing the Offset, Designed Using TRANSYT-7F, on the PI of the Hypothetical Artery Determined Using the Estimated Variation Model

Design Cycle (Sec)	IOVD (%)	TRANSYT PI (Design) Heavy Outbound	Average	Heavy Inbound
75	-50	25.0	31.2	31.9
	-25	29.3	33.1	33.7
	0	38.3	36.6	37.3
	25	34.9	28.7	28.9
	50	30.0	24.8	24.5
125	-50	42.9	44.0	49.1
	-25	48.7	48.0	52.1
	0	61.0	58.9	59.9
	25	54.2	50.7	48.7
	50	51.6	47.4	46.5
150	-50	104.2	105.2	111.5
	-25	112.5	110.9	115.6
	0	145.7	142.3	142.7
	25	118.5	114.4	112.4
	50	114.5	109.6	103.8

NOTE: Underlining indicates that the offset plan which produced that PI should be selected for this IOVD.

Table 3.6 Offset Transfer Thresholds Determined for the Hypothetical Artery Based on the Estimated Variation; the Offsets were Designed Using TRANSYT-7F

Design Cycle (Sec)	IOVD for Transfer (%)	
	Offset 1[a] - Offset 2[b]	Offset 2[b] - Offset 3[c]
75	-8	35
125	-35	8
150	-40	4

[a]The heavy outbound design.

[b]The average design.

[c]The heavy inbound design.

equally, it favored one direction at the expense of the other because this solution would produce shorter delays and fewer stops. The way TRANSYT-7F decided to pass the band for the balanced situation was dependent on the volume level on the artery. TRANSYT-7F might give a different proportion of the progression to a given direction depending on the AVL and thus on the design cycle length. The thresholds to transfer between different TRANSYT-7F offset designs were dependent on how close the design for the balanced condition was to each of the other two designs. Since this was a function of cycle length, different offset transfer thresholds were obtained for different cycles.

Step 5: Design of split plans

This step and Step 6 were only necessary if the TRSP selection of split plans was permitted for one or more intersections in the system.

For each design cycle, three split plans were designed for light, average, and heavy cross street volume conditions using TRANSYT-7F.

First, SAS was used to obtain the mean and the standard deviation of the CAVD during the time period for which the counts were available. The mean value, plus and minus one standard deviation, was used to establish the CAVD's used for the design.

To create the above three conditions in a system, the variable $LLAVL_i$ was defined first to be the lower limit of

the AVL interval for which the design cycle i was selected. Then the three conditions chosen for the design were obtained from a system, with AVL equal to $LLAVL_i$ and IOVD equal to zero, by varying the CAVD. The estimated variation model was then used to produce TRANSYT-7F input files with these conditions.

When obtaining the split plans for a given cycle, the offset plan was constrained to the average offset plan since the TRSP split plan selection is independent of the offset plan selection. This can be accomplished in TRANSYT-7F by grouping all the nodes together. TRANSYT-7F will optimize the splits keeping the offset constant. Versions of TRANSYT-7F prior to Release 6 do not allow optimization of grouped node splits (8). For those nodes, where the TRSP split plan selection was disabled, the splits should be constrained to that associated with the average offset plan for that node as obtained from Step 4. This was done because at those intersections the splits would be chosen based on the offset plan in effect rather than on CAVD.

Initial splits must be provided for grouped nodes in TRANSYT-7F optimization runs. A good initial solution is important because of the possibility of reaching a local optimum solution. Thus, for each traffic condition investigated, preliminary TRANSYT-7F optimization runs were performed first without grouping the nodes to obtain preliminary split plans. During these runs, the initial phase

durations were based on the concept of equal degree of saturation on the critical conflicting links at each node. Then, the preliminary split plans were used as inputs to the final TRANSYT-7F runs in which the nodes were grouped.

Example. Three split plans were designed for the four-intersection hypothetical artery. Since the TRSP split plan selection was permitted for all intersections, the splits for the four intersections were optimized.

The mean and the standard deviation of the CAVD in the system were computed as 16% and 16.2%, respectively. When obtaining the three CAVD's for split plan designs, a ceiling was imposed on the upper limit of the cross street volume to ensure that no volume exceeded its own reference volume. The three split plans were designed for zero, 14% and 28% CAVD. Since using a heavy cross street condition for the 150-second cycle was not possible because it would result in cross street volumes above the 100% reference volumes, only two split designs were determined for this cycle.

Step 6: Determination of split switching thresholds

TRANSYT-7F simulation runs were performed to evaluate the three split plans for each cycle under different CAVD conditions. These conditions were produced in the same manner used to produce the three CAVD conditions used for the design. Again, the estimated variation model was used to produce TRANSYT-7F input files for these conditions. The

offset plan used in TRANSYT-7F simulation was the offset design for the average condition obtained in Step 3 above.

For a given CAVD, the design split plan that should be selected for implementation is the one that produced the minimum PI compared to the other split plans of that cycle. When the controlled change in CAVD, resulted in the selection of a new split plan, a linear interpolation, similar to that utilized in offset threshold determination, was used to obtain the switching threshold between the old and the new selected split plans.

Example. Split plan transfer thresholds were determined for the four-intersection hypothetical artery. Table 3.7 shows the performances of the split plans with different CAVD values. The linear interpolation was used to obtain the transfer thresholds based on the results presented in this table. The interpolation results presented in Table 3.8 indicated that there were variations in split thresholds from one cycle to another.

Table 3.7 The Effect of Changing the Split Design on the PI of the Hypothetical Artery Determined Using the Estimated Variation Model

Design Cycle (Sec)	CAVD (%)	TRANSYT PI (Split Design) Light Cross Street	Medium Cross Street	Heavy Cross Street
	0	<u>29.4</u>	31.1	33.0
	7	33.5	<u>33.1</u>	34.6
75	14	42.9	<u>35.2</u>	36.6
	21	62.0	38.6	<u>38.3</u>
	28	91.4	46.8	<u>40.9</u>
	0	<u>36.9</u>	38.0	41.4
	7	41.8	<u>40.5</u>	43.3
125	14	55.9	<u>43.7</u>	45.7
	21	78.3	48.2	<u>47.9</u>
	28	111.9	62.2	<u>51.2</u>
	0	<u>58.8</u>	63.7	-
150	7	<u>66.8</u>	67.7	-
	14	95.4	<u>72.2</u>	-

NOTE: Underlining indicates that the split plan which produced that PI should be selected for this CAVD.

Table 3.8 Split Transfer Thresholds Determined for the Hypothesized Artery Based on the Estimated Variation

Design Cycle (Sec)	CAVD for Transfer (%)	
	Split 1[a] - Split 2[b]	Split 2[b] - Split 3[c]
75	6	19
125	3	20
150	8	-

[a]The light cross street design.

[b]The medium cross street design.

[c]The heavy cross street design.

CHAPTER FOUR
DEVELOPMENT OF A THRESHOLD SELECTION MODEL BASED ON ASSUMED VARIATION

Introduction

Chapter Three presented a method for determining transfer thresholds for the normal TRSP operation of a closed loop system. An important part of that method was the estimation of the turning movement volumes in the network based on detector measurements. A model referred to as the estimated variation model was developed and used for this purpose.

However, the estimated variation model demanded a substantial computational effort in estimating the turning movement volumes in the system. The least squares adjustment and the multiple linear regression which were used in the model required extensive use of SAS and SAS/IML. The estimated variation model also required reliable count data that might not always be available.

A simpler model, referred to as the assumed variation model, was developed in this study as an alternative to the estimated variation model. Instead of estimating link volumes from detector measurements, the assumed variation model approximates the variations in link volumes by using detector volume variations.

This chapter first presents the assumed variation model concept and the model development. Secondly, the use of this model in the threshold determination is discussed. Finally, an application of the threshold determination model, based on both the estimated and the assumed variation models, is presented.

Assumed Variation Model

Model Concept

The basic technique used in the assumed variation model is to approximate link volume variations in the system based on detectorized approach volume variations. The model calculates the nondetectorized link volume variation in a given movement direction based on the proportional change in detector volumes in that direction. It presupposes that within a given traffic pattern, link volumes in any direction of travel (inbound, outbound, or cross street) are at equal proportions of their reference volumes. Thus, if the volume levels on the detectorized approaches in a given direction are at some average proportion of their reference volumes, then the volume on each link in that direction can be calculated by multiplying the link reference volume by that average proportion.

The reference volumes were calculated for every link in the system using equation (3.1). The assumed variation model does not require the balancing of the turning movement

volumes in the system. Thus, the count data (without adjustment) were used in reference volume calculations.

The basic idea of the assumed variation model is based on the TRSP operation of the closed loop system. The TRSP selection of cycles, offsets, and splits in this system assumes that movements in each direction of travel are highly correlated with the detectorized approaches in that direction. Thus, any shift in detectorized approach volumes, in a given direction, should represent a shift in the volumes on all the approaches with the same direction.

As discussed in the previous chapter, the TRSP selection of split plans can be disabled on one or more intersections in the system. In this case, the cross street movement volumes on those intersections are no longer assumed to be correlated with the volumes of the cross street detectorized approaches. Thus, the model keeps the volume of these movements constant relative to the detectorized movement volumes on the artery when the CAVD is changed to determine the split plan thresholds.

Model Development

In this study, the assumed variation model was used to calculate the turning movement volumes required to run TRANSYT-7F and PASSER-II, for all conditions investigated. These conditions were produced by varying the AVL, the CAVD, and the IOVD in the system. As explained in Chapter Three, this was achieved by multiplying the reference volumes of

the detectorized approaches in each direction by appropriate multipliers. Based on the concept of the assumed variation model, the turning movements in the system can be calculated by multiplying the reference volumes of the links in a given direction by the reference volume multiplier of the detectorized approaches in that direction.

Figure 4.1 presents an illustration of the computational technique of the assumed variation model. Figure 4.1(a) shows a condition in a system in which the volume on each detectorized approach is equal to its reference volume. In this case, AVL is 100%, CAVD is zero, and IOVD is zero and, thus, the volume multipliers for all directions are one. In Figure 4.1(b), the AVL is modified by multiplying the reference volume on all detectorized approaches by 0.9. Figure 4.1(c) shows a traffic condition in which the AVL is 90%, the IOVD is 50% and the CAVD is zero. In all three traffic conditions, each link volume was calculated by multiplying the link reference volume by the volume multiplier of the detectorized approaches that had the same direction of the link.

To generate TRANSYT-7F input files for different traffic conditions in the system, an AAP data deck was coded for the artery with the volume on each link equal to the reference volume of the link. Then, a program written for this study was used to apply the required variation by multiplying the coded link volumes by factors which were constants

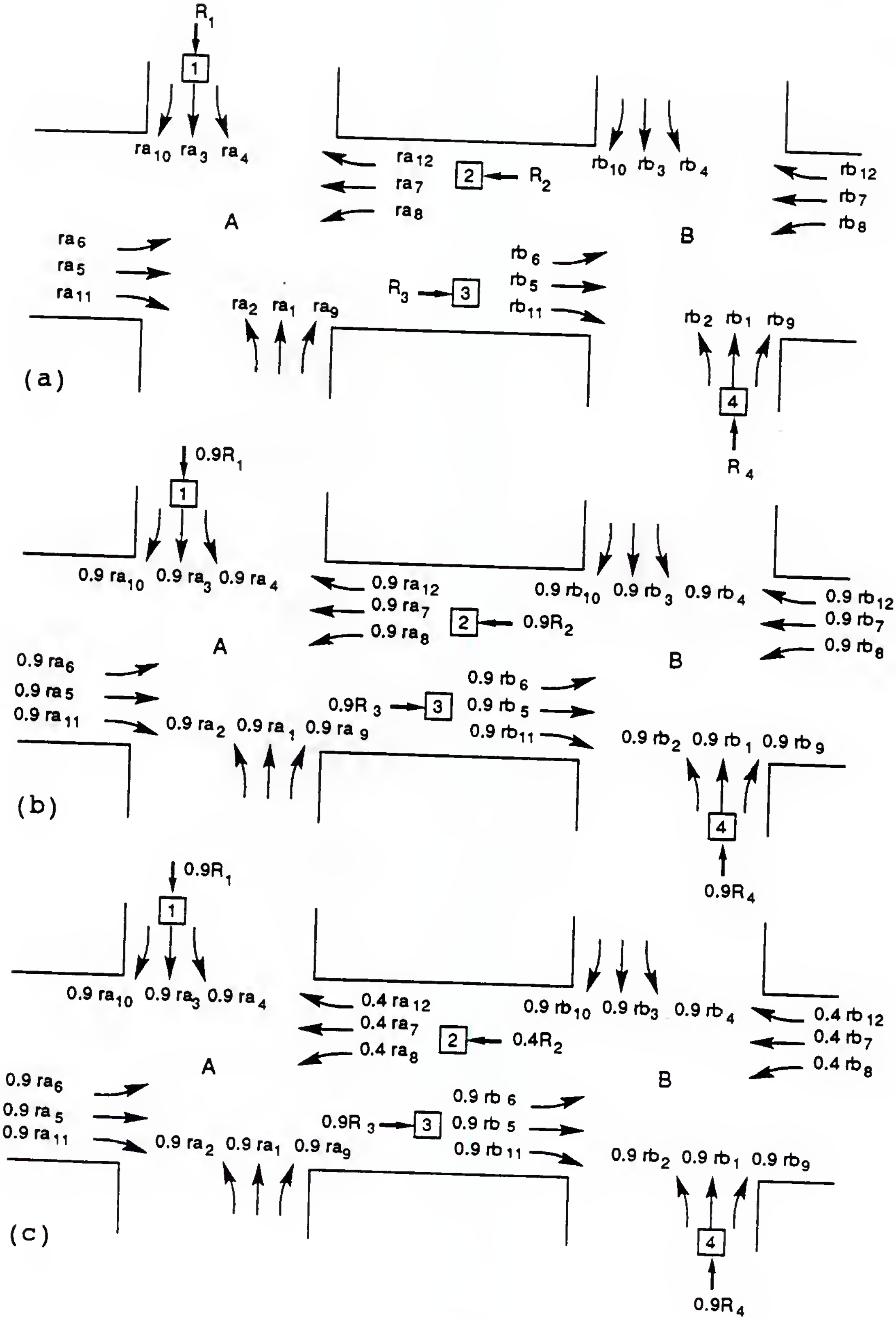
Figure 4.1. Estimating the link volumes for an arterial system using the assumed variation model.

(a) Estimating the link volumes for an artery with 100% AVL, zero IOVD, and zero CAVD.

(b) Estimating the link volumes for an artery with 90% AVL, zero IOVD, and zero CAVD.

(c) Estimating the link volumes for an artery with 90% AVL, 50% IOVD, and zero CAVD.

NOTE: In this figure R_i represents the reference volume for detectorized approach i, and ra_j and rb_j represents the reference volumes for turning movement i on intersections A and B, respectively.



R1
1
ra10 ra3 ra4
ra12
ra7
ra8
2
R2
rb10 rb3 rb4
rb12
rb7
rb8
A
B
ra6
ra5
ra11
ra2 ra1 ra9
R3
3
rb6
rb5
rb11
rb2 rb1 rb9
4
R4
(a)
0.9R1
1
0.9 ra10 0.9 ra3 0.9 ra4
0.9 ra12
0.9 ra7
0.9 ra8
2
0.9R2
0.9 rb10 0.9 rb3 0.9 rb4
0.9 rb12
0.9 rb7
0.9 rb8
A
B
0.9 ra6
0.9 ra5
0.9 ra11
0.9 ra2 0.9 ra1 0.9 ra9
0.9R3
3
0.9 rb6
0.9 rb5
0.9 rb11
0.9 rb2 0.9 rb1 0.9 rb9
4
0.9R4
(b)
0.9R1
1
0.9 ra10 0.9 ra3 0.9 ra4
0.4 ra12
0.4 ra7
0.4 ra8
2
0.4R2
0.9 rb10 0.9 rb3 0.9 rb4
0.4 rb12
0.4 rb7
0.4 rb8
A
B
0.9 ra6
0.9 ra5
0.9 ra11
0.9 ra2 0.9 ra1 0.9 ra9
0.9R3
3
0.9 rb6
0.9 rb5
0.9 rb11
0.9 rb2 0.9 rb1 0.9 rb9
4
0.9R4
(c)

for the links that had the same direction of travel. These factors were the reference volume multipliers of the detectorized approaches in the movement direction of the links.

Threshold Determination

The transfer thresholds were determined based on the assumed variation model using the same techniques illustrated in Chapter Three. The only alteration to that technique was the method used to calculate the turning movement volumes in the system based on detectorized approach volumes. The assumed variation model represents an easy method to obtain the turning movement volumes compared to the more complex model (the estimated variation model). To determine the signal timing parameter thresholds, the AVL, the IOVD and the CAVD in the system had to be varied as explained in the previous chapter. Then, the design parameters were evaluated with these conditions using TRANSYT-7F files created based on the assumed variation model. The cycles, offsets and splits thresholds were then determined as explained in the previous chapter.

Application of the Threshold Selection Model Based on the Estimated and the Assumed Variations

This section presents an application of the threshold determination using the estimated variation model first, then the assumed variation model. The artery chosen as an example for this purpose was Richmond Road in Lexington, KY. Richmond Road is an east-west artery with 18 intersections.

A subsection of nine intersections (16 links) was chosen for this study.

This practical example was used to demonstrate the application of the threshold selection model because the more trivial and hypothetical examples presented in the previous chapter would not make a very convincing demonstration. The Lexington artery was used because of the availability of field data, despite the fact that the Lexington control system differs from the system which is used as a model for this study.

The selected arterial system passes through residential, commercial and industrial zones. In this artery, there were three system sensors on inbound (west bound) approaches, four sensors on outbound (east bound) approaches and three sensors on cross streets. The locations of these sensors are presented in Figure 4.2.

The traffic counts available covered six hours during the day representing a.m., noon, and p.m. peaks. These counts were obtained at 15-minute intervals for every intersection in the system. It was noted that the six hours covered by the count data might not be enough to reflect the total variations in the traffic conditions during the day. However, it was assumed that the data were good enough for the purpose of this demonstration.

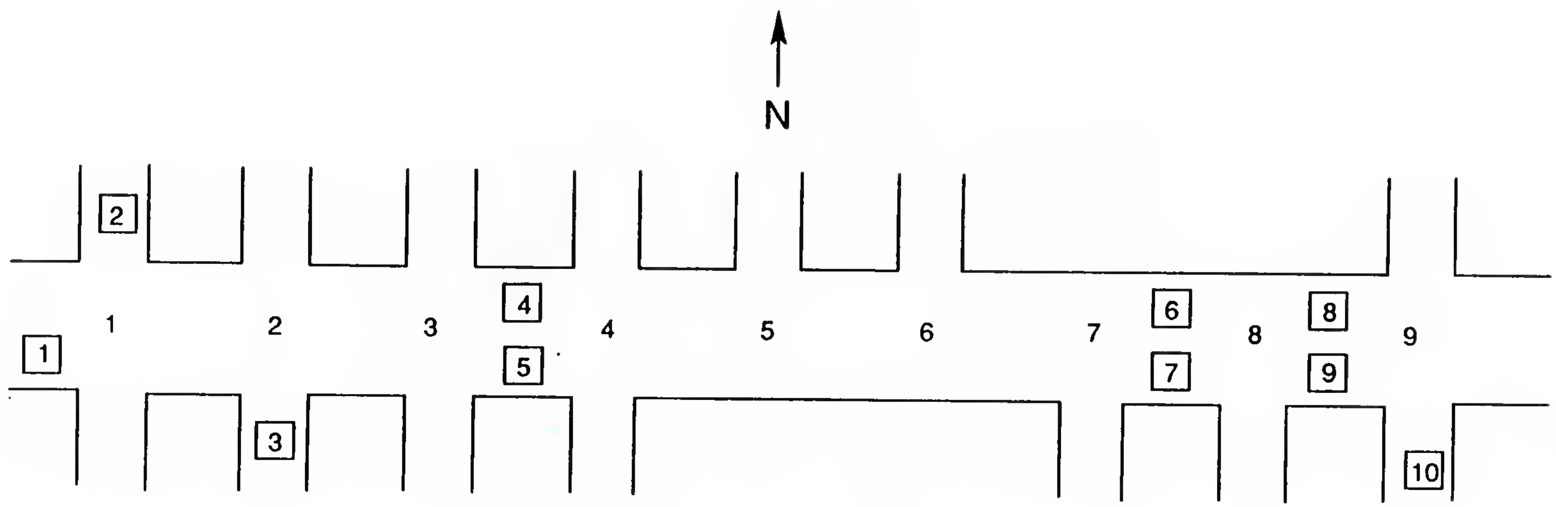


Figure 4.2. The location of the system sensors in the nine-intersection Lexington artery.

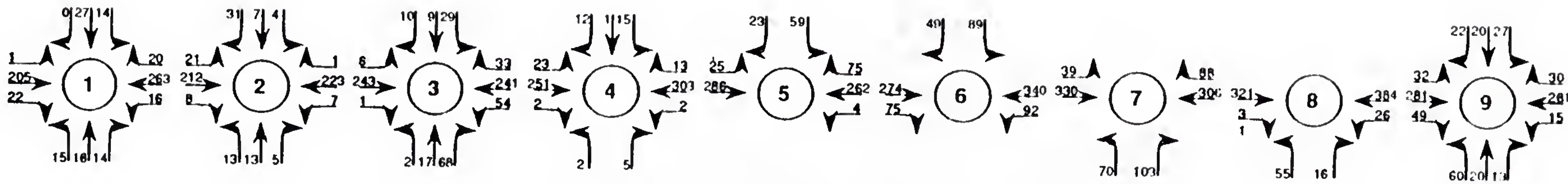
NOTE: Each square in this figure represents a system sensor location. The number inside the square is the sensor number.

No attempt was made to optimize the phasing sequences. The existing phase sequences were used in the timing plan development.

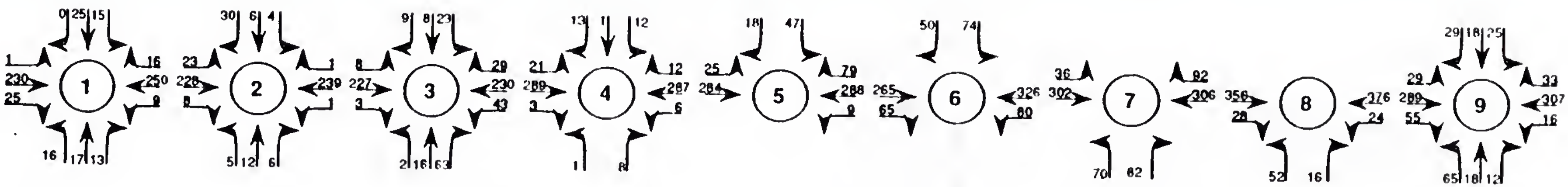
First, thresholds were selected using the estimated variation model to obtain the turning movement volumes in the system. The least squares adjustment model described in Chapter Three was used to adjust the traffic counts for each time period. An example of the traffic flows in the artery, before and after the adjustment, for a specific count period is presented in Figure 4.3. Multiple linear regression was then used to derive the linear relationships between the nondetectorized approach volumes and the detectorized approach volumes.

The correlations between the approach volumes in the system were determined. These correlations revealed that based on the six hours of data available, the movements in any given movement direction along the artery were highly correlated. However, the cross street movements were also correlated with the arterial movements.

Table 4.1 presents the results of the regression analysis performed based on the adjusted traffic counts. It is clear from this table that the R^2 values for the arterial movements were high. However, the R^2 values for the cross street movements were lower. The volumes on the cross street approaches were generally light compared to the volumes on the artery. It is believed that errors in



(a)



(b)

Figure 4.3. The link volume on the Lexington artery for period 1300 before and after the adjustment.

(a) Before the adjustment.

(b) After the adjustment.

Table 4.1 The Estimation Equations for the Volumes on the Nondetectorized Approaches of the Lexington Artery

Inter-section	Approach	Estimation Equation	R^2
1	Northbound	$(UNDET_1)^{1/2} = 3.33 + 0.071\ DET_3 + 0.037\ DET_{10}$	0.59[a]
	Southbound	Detectorized Approach (2)[b]	--
	Eastbound	Detectorized Approach (1)[b]	--
	Westbound	$(UNDET_2)^{1/2} = 8.27 + 0.027\ DET_4$	0.86
2	Northbound	Detectorized Approach (3)[b]	--
	Southbound	$(UNDET_3)^{1/2} = 2.98 + 0.054\ DET_3 + 0.030\ DET_{10}$	0.59[a]
	Eastbound	$(UNDET_4)^{1/2} = 7.33 + 0.027\ DET_5$	0.98
	Westbound	$(UNDET_5)^{1/2} = 8.33 + 0.023\ DET_4$	0.88
3	Northbound	$(UNDET_6)^{1/2} = 5.03 + 0.015\ DET_5$	0.90
	Southbound	$(UNDET_7)^{1/2} = 1.81 + 0.011\ DET_9$	0.91
	Eastbound	$(UNDET_8)^{1/2} = 7.40 + 0.024\ DET_5$	0.98
	Westbound	Detectorized Approach (4)[b]	--

4	Northbound	$(UNDET_9)^{1/2} = 1.90 + 0.004\ DET_9$	0.56
	Southbound	$(UNDET_{10})^{1/2} = 3.22 + 0.008\ DET_7$	0.68
	Eastbound	Detectorized Approach (5)[b]	--
	Westbound	$(UNDET_{11})^{1/2} = 9.36 + 0.026\ DET_4$	0.98
5	Southbound	$(UNDET_{13})^{1/2} = 3.13 + 0.013\ DET_7$	0.91
	Eastbound	$(UNDET_{14})^{1/2} = 8.31 + 0.029\ DET_5$	0.98
	Westbound	$(UNDET_{15})^{1/2} = 11.06 + 0.026\ DET_4$	0.96
6	Southbound	$(UNDET_{16})^{1/2} = 6.65 + 0.011\ DET_9$	0.78
	Eastbound	$(UNDET_{17})^{1/2} = 8.15 + 0.026\ DET_7$	0.98
	Westbound	$(UNDET_{18})^{1/2} = 11.42 + 0.028\ DET_4$	0.96
7	Northbound	$(UNDET_{19})^{1/2} = 5.68 + 0.016\ DET_4 + 0.005\ DET_9$	0.92[c]
	Eastbound	$(UNDET_{20})^{1/2} = 7.72 + 0.026\ DET_7$	0.98
	Westbound	Detectorized Approach (6)[b]	--

Table 4.1--Continued

Inter-section	Approach	Estimation Equation	R^2
8	Northbound	$(UNDET_{21})^{1/2} = 5.61 + 0.004\ DET_9$	0.34
	Eastbound	Detectorized Approach (7)[b]	--
	Westbound	Detectorized Approach (8)[b]	--
9	Northbound	Detectorized Approach (10)[b]	--
	Southbound	$(UNDET_{22})^{1/2} = 6.26 + 0.008\ DET_9$	0.70
	Eastbound	Detectorized Approach (9)[b]	--
	Westbound	$(UNDET_{23})^{1/2} = 10.27 + 0.020\ DET_8$	0.88

[a] The correlation between DET_3 and DET_{10} is 0.265.

[b] The numbers between brackets represent the number of the detectorized approach.

[c] The correlation between DET_4 and DET_9 is -0.173.

estimating light movement volumes have less effect on plan design and evaluation as compared with errors in estimating heavy movement volumes.

In addition, it is apparent from Table 4.1 that large proportions of the cross street movements were dependent on the detectorized movements on the artery. An essential requirement for any traffic responsive split plan selection is that the cross street movements should be more correlated with the cross street detectors than with the arterial detectors. Thus, based on the six hours data available, one can conclude that minimal benefit would be obtained from the implementation of the TRSP split plan selection. In this example, the transfer thresholds were obtained only for the cycles and the offsets.

The equations of Table 4.1 were used to estimate the volumes on the nondetectorized approaches based on detectorized volumes for each traffic condition investigated when obtaining the cycle and the offset thresholds as explained before.

It should be noted that in determining thresholds it might be useful were the user to exclude minor links from the PI calculation. In that case, the model will focus on the major links when obtaining thresholds. This can be accompanied in TRANSYT-7F by entering zero weights for the minor links on the delay weight modification card and the stop penalty modification card.

The minimum cycle length that satisfied the sum of the minimum greens was 70 seconds. The maximum cycle length obtained using TRANSYT-7F was 150 seconds. Five cycle lengths were selected for investigation between the minimum and the maximum cycle lengths. These cycle lengths were 70, 90, 110, 130 and 150 seconds.

Table 4.2 shows the performance of these cycles with different AVLs in the system. This table shows that the 130-second cycle was optimum only at the 90% AVL where it produced a PI that was very close to that of the 150-second cycle. It was clear that the 130-second cycle was the least significant among the other cycle lengths. Thus, it was decided to exclude this cycle from the design and to use the other four cycles as the design cycles. Four is the maximum number of cycles that can be programmed in the normal operation of the TRSP. The cycle transfer thresholds were determined as explained previously and are shown in Table 4.3.

Three offset plans were designed for each of three design cycles. TRANSYT-7F was used to design offset plans for heavy inbound, average and heavy outbound volume conditions. The effect of the offset plans on the PI of the artery with different IOVD is presented in Table 4.4. The thresholds derived from these results are presented in Table 4.5. This table indicates that the transfer thresholds selected were different for different cycles.

Table 4.2 The Effect of Changing the Cycle Length on the PI of the Lexington Artery Determined Using the Estimated Variation Model

AVL %	TRANSYT PI (Cycle) 70 Sec	90 Sec	110 Sec	130 Sec	150 Sec
40	<u>92.5</u>	94.5	98.3	98.6	100.6
50	<u>124.9</u>	124.9	141.6	141.8	139.7
60	224.7	<u>182.5</u>	197.1	184.0	194.2
70	401.9	<u>251.1</u>	268.8	274.3	294.4
80	1003.9	571.1	<u>497.1</u>	510.0	619.9
90	1776.6	1180.9	1067.2	1034.5	<u>1035.6</u>
100	2985.4	2127.0	1977.4	1880.8	<u>1820.7</u>

NOTE: Underlining indicates that the cycle length which produced that PI should be selected for this AVL.

Table 4.3 The Cycle Transfer Thresholds Determined Using the Estimated Variation Model for the Lexington Artery

Shorter Cycle (Sec)	Longer Cycle (Sec)	AVL to Transfer (%)
70	90	50
90	110	73
110	150	89

Table 4.4 The Effect of Changing the Offset Design on the Performance of Lexington Artery Determined Using the Estimated Variation Model

Design Cycle (Sec)	IOVD (%)	TRANSYT PI (Design) Heavy Outbound	Average	Heavy Inbound
	-50	<u>144.4</u>	150.3	173.8
	-25	179.9	<u>178.8</u>	194.4
90	0	264.8	<u>250.6</u>	258.3
	25	204.4	186.3	<u>179.8</u>
	50	171.5	149.3	<u>136.9</u>
	-60	<u>294.8</u>	306.4	329.7
	-30	<u>400.7</u>	402.1	418.6
110	0	795.4	<u>789.3</u>	798.3
	30	431.4	424.5	<u>408.9</u>
	60	332.3	308.8	<u>294.2</u>
	-70	<u>1034.4</u>	1062.6	1085.2
	-50	<u>1112.7</u>	1127.5	1151.8
	-25	1350.6	<u>1350.2</u>	1372.8
150	0	1893.5	<u>1873.0</u>	1890.7
	25	1031.7	1012.7	<u>1010.1</u>
	50	745.3	713.9	<u>706.5</u>
	70	668.6	630.8	<u>622.8</u>

NOTE: Underlining indicates that the offset plan which produced that PI should be selected for this IOVD.

Table 4.5 Offset Transfer Thresholds Determined Using the Estimated Variation Model for the Lexington Artery

Design Cycle (Sec)	IOVD for Transfer (%)	
	Offset 1[a] - Offset 2[b]	Offset 2[b] - Offset 3[c]
90	-29	13
110	-24	11
150	-26	22

[a]The heavy outbound design.

[b]The average design.

[c]The heavy inbound design.

Next, thresholds were determined based on the assumed variation. The assumed variation model presented in this chapter was used to produce a TRANSYT-7F input file for each condition investigated.

Five cycle lengths were chosen between the minimum and the maximum cycle lengths. These cycle lengths were 70, 90, 110, 130, and 150 seconds. The performances of these cycles with different AVLs are presented in Table 4.6. This table indicates that the 130-second cycle was not selected at any AVL investigated. Accordingly, the 130-second cycle was excluded and the four cycle lengths used for design were 70, 90, 110, and 150 seconds.

The cycle thresholds determined using the assumed variation model are shown in Table 4.7. These thresholds were very close to those obtained using the estimated variation model and presented in Table 4.3.

Again, three offset plans were designed using TRANSYT-7F for each of three design cycles. The performance of these plans with different IOVD in the system and the transfer thresholds between these plans are shown in Tables 4.8 and 4.9, respectively. It is clear from Table 4.8 that the transfer thresholds selected were different for different cycles. This could be attributed at least in part to the difference in the offset designs at zero IOVD for different cycles. As explained in Chapter Three, TRANSYT-7F might result in giving a different proportion of the progression

Table 4.6 The Effect of Changing the Cycle Length on the PI of the Lexington Artery Determined Using the Assumed Variation Model

AVL %	TRANSYT PI (Cycle)				
	70 Sec	90 Sec	110 Sec	130 Sec	150 Sec
50	<u>143.8</u>	151.5	169.5	177.5	194.0
60	257.7	<u>224.6</u>	232.0	235.2	250.4
70	484.8	<u>323.4</u>	332.7	352.9	374.6
80	1136.6	704.5	<u>620.6</u>	721.0	771.7
90	1945.9	1366.8	<u>1148.1</u>	1150.4	1164.8
100	2896.1	2206.0	2038.3	1924.3	<u>1886.4</u>

NOTE: Underlining indicates that the cycle length which produced that PI should be selected for this AVL.

Table 4.7 The Cycle Transfer Thresholds Determined Using the Assumed Variation Model for the Lexington Artery

Shorter Cycle (Sec)	Longer Cycle (Sec)	AVL to Transfer (%)
70	90	53
90	110	72
110	150	92

Table 4.8 The Effect of Changing the Offset Design on the Performance of the Lexington Artery Determined Using the Assumed Variation Model

Design Cycle (Sec)	IOVD (%)	TRANSYT PI (Design) Heavy Outbound	Average	Heavy Inbound
90	-50	<u>232.0</u>	249.7	265.5
	-25	<u>266.9</u>	272.7	288.4
	0	340.3	<u>330.0</u>	344.9
	25	250.7	<u>235.5</u>	246.0
	50	221.5	<u>195.0</u>	195.4
	60	209.7	181.8	<u>180.9</u>
110	-50	<u>658.2</u>	674.6	690.7
	-25	<u>818.1</u>	822.1	835.2
	0	1147.3	<u>1130.7</u>	1151.6
	25	718.8	710.7	<u>708.7</u>
	50	592.6	585.0	<u>574.4</u>
150	-75	<u>1202.1</u>	1204.0	1246.3
	-50	1290.0	<u>1286.6</u>	1319.6
	-25	1565.7	<u>1565.8</u>	1623.7
	0	1907.0	<u>1892.9</u>	1926.8
	25	1442.0	<u>1438.2</u>	1440.5
	50	1204.5	1197.9	<u>1186.1</u>

NOTE: Underlining indicates that the offset plan which produced that PI should be selected for this IOVD.

Table 4.9 Offset Transfer Thresholds Determined Using the Assumed Variation Model for the Lexington Artery

Design Cycle (Sec)	IOVD for Transfer (%)	
	Offset 1[a] - Offset 2[b]	Offset 2[b] - Offset 3[c]
90	-15	53
110	-20	23
150	-65	29

[a]The heavy outbound design.

[b]The average design.

[c]The heavy inbound design.

to a given direction, at zero IOVD, depending on the AVL in the system.

The offset thresholds determined, based on the estimated variations and the assumed variations, shown in Tables 4.5 and 4.9, respectively, were different. This could also be related to the different designs of the offset plans that were produced by TRANSYT-7F using the two models since these models produced different volumes in the system.

Finally, it should be noted that existing versions of the off-line signal timing programs were used to design and evaluate signal timing parameters in this example. Some problems were encountered when using these programs, problems which could affect the results presented in this example. In Chapter Five, an investigation of these problems will be presented.

CHAPTER FIVE
INVESTIGATIONS OF PROBLEMS IN OFF-LINE SIGNAL TIMING PROGRAMS

Introduction

The threshold determination models presented in the previous chapters require the use of available off-line signal timing programs. The AAP, TRANSYT-7F, and PASSER-II were used extensively in various steps of the models to design and evaluate the signal timing plans. These programs are among the off-line signal timing models most accepted by the traffic engineering community. They have yielded adequate signal timing plans for both computerized and noncomputerized traffic control systems.

However, the use of these signal timing programs in this study placed a higher demand on the models than their normal utilization. Good design and evaluation of signal timing parameters were required to obtain the thresholds. Sometimes this could not be achieved using the available versions of the models. Thus, it was necessary to investigate problems and inconsistencies that might exist in the three signal timing models used in this study. This investigation was not intended to seek out all of the problems in these programs. The objective was simply to identify the

problems that were experienced when using the programs in this study.

Some of the inconsistencies found were addressed in experimental versions of the programs. These experimental versions were then tested. The results are discussed in this chapter. Recommendations to solve the remaining difficulties identified by the programs are also presented.

Problems Associated with TRANSYT-7F

TRANSYT-7F (Release 6) was used in this study for signal timing plan design and evaluation. This section describes problems experienced with the program in this study.

An Investigation of the Permitted Movement Model

Sometimes, it was clear that the designs suggested by TRANSYT-7F could be modified to produce timing plans with lower PIs. One of the examples illustrating this was observed when determining the thresholds for a four-intersection Gainesville, FL artery. Some of the turning movements in that artery involved permitted plus protected left turn treatment.

When optimizing the signal timing plan for a specific traffic condition in the system, it was intuitively apparent that the plan suggested by TRANSYT-7F could be improved. An iterative trial and error procedure which involved manual modification of the splits, and reoptimizing the offsets after each modification produced a much lower PI. The PI

for the plan obtained from the TRANSYT-7F optimization was 335.6. The trial and error modification procedure was able to reduce the PI to 300.4, a reduction slightly greater than 10%.

Another indication of a problem with TRANSYT-7F is seen in the results presented in Table 5.1. In TRANSYT-7F, cycle length selection can be accomplished automatically by evaluating a range of cycle lengths. TRANSYT-7F uses a quick optimization in this evaluation. The use of the quick optimization rather than the normal optimization, which is the default optimization type when optimizing the offsets and the splits, reduces the execution time of the program.

Although the MOEs produced by the traffic flow model are less accurate in a quick cycle length evaluation, TRANSYT-7F must still select the best cycle length based on relative ranking of these results (8). Table 5.1 compares the results obtained from a quick cycle evaluation with those obtained when optimizing each cycle individually using a normal optimization run. The example used is the same four-intersection Gainesville artery mentioned above. The table shows that the best cycle according to the quick optimization was the worst cycle according to the normal optimization. This difference suggested further that there is a problem with TRANSYT-7F.

Table 5.1 A Comparison between the Results Obtained From a Quick Cycle Evaluation and Those Obtained From Normal Optimization Runs Using TRANSYT-7F, Release 6

Cycle Length (Sec)	TRANSYT PI	
	Quick Cycle Evaluation	Normal Optimization Runs
85	331.3	329.2
90	322.2	322.7
95	319.1	330.8
100	326.6	323.2
105	320.1	316.6
110	327.7	314.8

The above examples were only two among many other observations suggesting that TRANSYT-7F had to be investigated for possible inconsistencies.

To understand the following investigation a brief description of the way TRANSYT-7F selects the timing plans is required.

TRANSYT distinguishes between three traffic flow patterns: IN, GO and OUT patterns.

The IN pattern is the arrival pattern computed for each step in the cycle. The GO pattern or the saturation flow output pattern is the flow rate at each step which would leave the stopline if there was enough traffic to saturate the green. The OUT pattern is the profile of the traffic leaving the stopline. It is usually equal to the GO pattern as long as the green is saturated. Otherwise, it is equal to the IN pattern for the duration of the effective green.

Subroutine HILLCL is the TRANSYT-7F hill climb optimization submodel (54). It iteratively changes the offsets or the splits by specific amounts and calls subroutine SUBPT to calculate a new PI. This new PI is compared with the previous value of the PI (before the changes) to determine whether the last change was an improvement.

If the model changes the offsets or the splits in one-second increments and then resimulates the system for that increment, it would be extremely time consuming. To overcome this problem a special application of the hill

climb concept, using different step sizes, is used by the program. The step sizes used are according to a list of optimization step sizes. A step can involve either offset change or split change.

Subroutine SUBPT is the traffic simulation model of TRANSYT-7F (54). This routine simulates traffic flow and calculates the MOEs and the PIs. One should distinguish between four types of simulation in the model. (Type three simulation is not relevant to this discussion.)

Type one simulation. In this type of simulation, all links are simulated. However, if permitted links are present, the permitted movement model in TRANSYT-7F is not used. Instead, the GO pattern used is the user coded (or default) maximum flow rate upper limit, which is based on the 1985 Highway Capacity Manual (55) (i.e., 1200 minus opposing flow).

Type two simulation. Only those links affected by the current change made in HILLCL are simulated. The resulting traffic flows are resimulated on downstream links subjected to a sensitivity parameter threshold value. For this purpose, the program compares the OUT pattern for a simulated link before and after the timing change. The degree of change in the OUT pattern is compared with the sensitivity parameter to decide whether or not new profiles for the next downstream links are calculated.

<u>Type four simulation</u>. In this simulation, the permitted movement model is implemented to resimulate the permitted links only. This takes into account the OUT patterns of the opposing flows.

<u>Type five simulation</u>. In this simulation all unopposed links are resimulated to correct the OUT patterns to the IN patterns which may have shifted somewhat in type four simulation.

In the current version of TRANSYT-7F, when an evaluation run is requested for a network with permitted movements, SUBPT performs a sequence of simulations which includes type one simulation followed by type four simulation followed by type five simulation.

When the run is an optimization run, SUBPT performs the same sequence of simulations (type one, then type two, then type five) to calculate the initial PI for the initial signal timing plan. Then, at signal i (initially the first signal on the optimization node list coded by the user), HILLCL increases the offset or a phase length (depending on the current step type) by an amount specified on the optimization step size list. Next, SUBPT performs a type two simulation and a new PI is compared with the previous value (before the last signal timing change) as follows.

1. If the new PI is less than the previous value, HILLCL continues to increase the offset (or the phase length) by the same amount as long as there is a decrease in

the PI. The PIs are calculated based on the type two simulation.

2. If the new PI is greater than the previous value, the program will decrease the offset (or the phase length) by the same amount and continue to decrease it by this amount as long as there is a decrease in the PI. The PIs are calculated based on type two simulation.

When no further improvement can be made by varying the offsets (or the splits) at this signal, the model goes to the next signal and repeats the process of changing the offset or the splits and resimulating. This is done for each signal in the network in turn for the same optimization step size.

After all the nodes in the system are processed in this manner, a resimulation is performed to calculate a new PI. This simulation is a type one simulation which simulates all the links in the network without the permitted movement model. The PI calculated from this simulation is compared with the old PI before any change was made using the current optimization step size. If the new PI is greater than the old PI, the program changes the timings back to the one before this step size.

The above optimization process is repeated for all the optimization step sizes. At the end of this process, the program performs type one simulation followed in sequential

order by types four and five simulations to report the final PI calculated for the selected timing plan.

The above procedure did not produce plans with minimum PI values when permitted movements existed due to the following two reasons.

1. The simulation performed after processing the offsets or the splits at all signals for a given step size is a type one simulation. This simulation is not good enough for comparison when permitted movements exist. Additional simulations (types four and five) following type one simulation might be necessary in this case.

2. Within each step size, a type two simulation is performed after changing the offset or the split at a given signal. This also might not be enough for the comparison when there are permitted turns in the system. Type two simulation does not use the permitted movement model in TRANSYT-7F. Instead, it calculates the GO pattern for the permitted turns in the same way used by type one simulation described above.

To investigate how the above two points might affect the performance of the model, two experimental versions of TRANSYT-7F, Release 6, were created. The first version was referred to as T7F145 and the second as T7F245. In version T7F145, at the end of each step size, additional simulations (types four and five), following type one simulation, were performed. Version T7F245 was created to consider both

points above. In addition to the modification made in version T7F145, types four and five simulations were performed after each type two simulation.

The two experimental versions were then tested. Table 5.2 shows a comparison of the results produced using the experimental versions with those obtained using the existing version of TRANSYT-7F, Release 6, and also the trial and error procedure described earlier in this section. The table indicates that version T7F145 produced lower PI compared to that produced using the existing version of the program. However, the trial and error procedure was still capable of producing a lower PI compared to that produced by T7F145. Version T7F245 produced the lowest PI compared to the other versions tested and also compared to the trial and error procedure.

As expected, the extra simulations required in the experimental versions of the program increased the computer time required. Table 5.2 shows the amount of increase in computer time for the example used. The runs were made on an IBM PC/AT compatible microcomputer with a math coprocessor. The increase is thought to be a function of how many permitted movements exist in the system.

Table 5.3 shows another indication of the improvement achieved using version T7F245. In this table, the comparisons presented in Table 5.1 were repeated using version T7F245.

Table 5.2 A Comparison of the Results Obtained Using the Two Experimental Versions of TRANSYT-7F with Those Obtained Using the Existing Version of TRANSYT-7F and the Trial and Error Procedure[a]

Method Used to Obtain Plan	TRANSYT PI	Computer Time[b] Minute/Node	Computer Time (%)
Using Existing Version of TRANSYT-7F	335.8	0.825	100
Using T7F145 Version	310.4	1.207	146
Using T7F245 Version	296.1	2.41	292
Using Trial and Error Procedure	300.4	-	-

[a]The example used in the comparison is a four-intersection Gainesville artery.

[b]The runs were made on an IBM PC/AT compatible microcomputer with 12 MHZ speed and a math coprocessor.

Table 5.3 A Comparison Between the Results Obtained From a Quick Cycle Evaluation and Those Obtained From Normal Optimization Runs Using the T7F245 Version of TRANSYT-7F

Cycle Length (Sec)	TRANSYT PI	
	Quick Cycle Evaluation	Normal Optimization Runs
85	328.6	325.6
90	316.4	316.7
95	307.4	312.5
100	310.7	311.6
105	304.3	299.1
110	301.0	293.8
115	294.7	288.3
120	294.8	283.8

Although the two types of optimization suggested different cycle lengths (115 seconds in the case of quick cycle evaluation and 120 seconds in the case of normal optimization), the difference was not as important as that observed when using the existing version of TRANSYT-7F.

An Investigation of the Procedure Used to Adjust the Upstream Flow

Another problem in TRANSYT-7F was noticed when working with the four-intersection east-west hypothetical artery presented in Chapter Three. In that artery, each internal link was fed by only one through upstream link since there were no turning movements from the cross streets.

Figure 5.1 presents the FPDs for a west-bound link on that artery. Figure 5.1(a) shows the FPD for a condition in which the flow on the upstream through link was 848 vph and the flow on the link was 963 vph. Thus, the upstream and the downstream flows were unbalanced in this case. The upstream and the downstream links had the same saturation flow rates (1636 vph). The figure shows that the maximum flow arrival on green was (1857 vph) which exceeded the saturation flow rate of the link (1636 vph). Thus, a queue was formed on green at the downstream link.

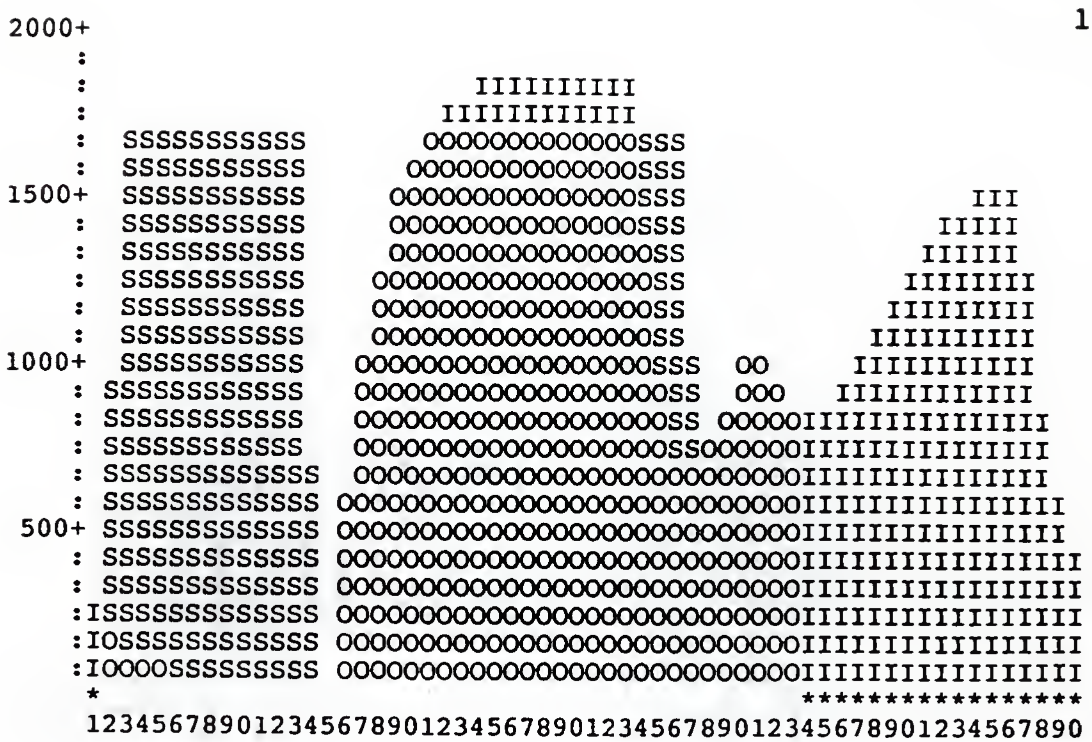
The arrival of a flow which exceeded the link saturation flow rate seemed surprising since the saturation flow rate of the upstream and the downstream links were equal.

To investigate this further, the flow rate on the upstream link was changed to a value equal to that of the

Figure 5.1. An illustration of the effect of the problem in TRANSYT-7F adjustment of the upstream flow on the flow profile diagram of a link.

(a) The upstream flow is less than the total flow on the link.

(b) The upstream flow is equal to the total flow on the link.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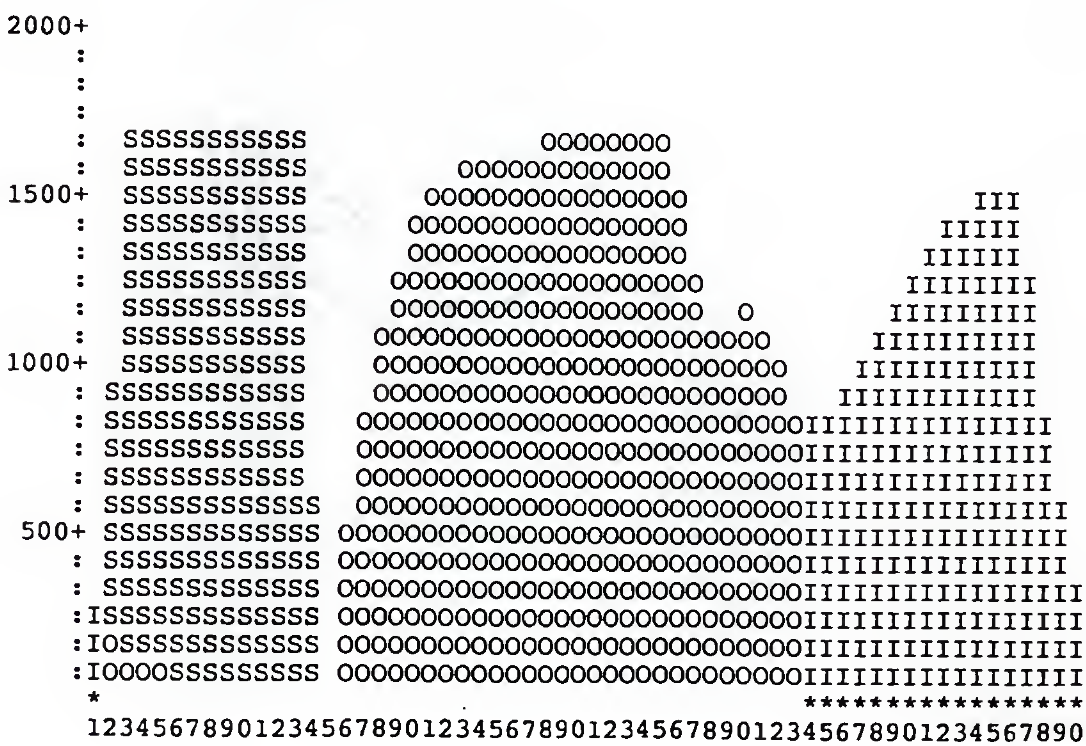
(a)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(b)

flow rate downstream (963 vph). Figure 5.1(b) shows that when the flow on the upstream link was equal to the flow on the downstream link, the maximum flow rate downstream did not exceed the saturation flow rate. In addition, the delay, the stops and the fuel consumption on the downstream link were reduced due to this modification as illustrated in Table 5.4. The above results suggested that TRANSYT-7F was inadequate when balancing the upstream and the downstream flows.

TRANSYT-7F uses a special formula, in subroutine CHKINP to adjust the input flow rates automatically to sum to the total flow rate of the link (54). The adjustment is calculated in this subroutine for each upstream-downstream links pair as follows

$$LENTF_{ji} = \frac{ENTF_{ji} \bullet IFLOW \bullet 500}{INFLOW \bullet LTFLOW} \qquad (5.1)$$

where

$ENTF_{ji}$ = the flow turning from the jth upstream link into link i before adjustment,

IFLOW = the total nonmid-block flow at link i,

LTFLOW = the total flow at the downstream end of the jth upstream link into link i, and

INFLOW = the sum of the raw input flows into link i before the adjustment.

An adjustment multiplier (RC) is calculated for each upstream link by dividing $LENTF_{ji}$ by 500 in subroutine

Table 5.4 A Comparison between the Measures of Effectiveness for Two Values of the Upstream Flow Rate at a Given Downstream Flow Obtained Using TRANSYT-7F

Flow Rate at Upstream Link (vph)	Flow Rate at Downstream Link (vph)	Total Time (veh-hr)	Average Delay (sec/veh)	Uniform Stops		Maximum Back of Queue (veh)	Fuel Consumption (gal)
				Number	Percent		
848	963	8.47	16.2	472	49	15	12.35
963	963	8.30	15.6	325	34	11	11.1

INPTRN. Then, for each step of the cycle, the OUT pattern from each upstream link is multiplied by its adjustment multiplier. This process has the effect of balancing the upstream flow with the downstream (nonmid-block) flow and adjusting to the upstream link's own flow (54).

The above adjustment works well as long as the OUT pattern of the upstream link, before and after the adjustments, is lower than its GO pattern.

If the OUT pattern, after the adjustment, exceeds the GO pattern, this means that the program is allowing more vehicles to leave the upstream stop line than the maximum number possible. On the other hand, when the OUT pattern, before the adjustment, equals the GO pattern, and RC is less than one, reducing the OUT pattern, by multiplying it by RC, is also not realistic. This is because the vehicles tend always to leave a queue at the maximum rate possible which is the GO pattern.

Now we can explain the reason for the problem indicated by Figure 5.1(a). RC is calculated to be 1.136 for the upstream link into the link with the FPD presented in that figure. If, at a given step, the OUT pattern of the upstream link, before the adjustment, was equal to the GO pattern, the adjustment resulted in an input flow equal to 1859 vph. The platoon of this flow arrived downstream at a rate of 1857 vph which was higher than the saturation flow rate downstream.

To solve this problem, a modification to the model is suggested as follows:

1. When the OUT pattern of the upstream link, after the adjustment, exceeds the GO pattern at a given step then the OUT pattern should be set equal to the GO pattern. The extra vehicles not adjusted for (the OUT pattern after the adjustment minus the GO pattern) should be added to the OUT patterns in later steps without causing the value of the OUT pattern to increase above the GO pattern at any step.

2. When the OUT pattern of the upstream link, before the adjustment, is equal to the GO pattern and RC is less than one, the OUT pattern should be set equal to the GO pattern. The vehicles not adjusted for should be subtracted from the OUT pattern in a later step (when the OUT pattern becomes lower than the GO pattern). However, the subtraction should not cause the OUT pattern at that step to fall below the IN pattern of the link. If, after this subtraction, there are still some vehicles not adjusted for (because of the IN pattern constrain), they should be subtracted from the OUT pattern in the previous step. This should be done even if the OUT pattern at this step is equal to the GO pattern.

Problems Associated with the Arterial Analysis Package

The AAP was used in this study to generate TRANSYT-7F and PASSER-II input files. The following are inconsistencies experienced with the AAP during this study.

1. The RIGHT card was added in Release 3 of the AAP program to permit explicit coding of right turns. The major result of this is to permit better modeling of all turning movements in the system, particularly for TRANSYT-7F. If no capacity is coded for a right turn movement, the program assumes that the right turn is sharing a lane with the through movement. In this case, the AAP is supposed to model one link for both the through and the right turn. The flow rates of the through movement and the right turn movement should be added to represent the flow on the combined link. When the right turn that has no capacity is feeding a downstream link, the combined link should be coded as an upstream link that is a source of flow to the downstream link. However, only the right turn flow from the combined link should be regarded as an input flow to the downstream link.

When generating TRANSYT-7F input files from AAP data decks, it was noticed that the right turn flows were not added to the through flows when zero capacities were coded for these right turns. However, the through links to which the right turns should have been added, were mapped as input links to the downstream links that were fed by the right turn movements. This deficiency was corrected in an experimental version of the program. In this version, the volume of a right turn that had no capacity was added to the volume of the through movement on the same approach.

The AAP maps the input flows in such a way that all upstream turning flows are assigned to the downstream through link. The upstream through flows are distributed among the downstream links. However, when a downstream link is a combined link of a through and a right turn movement (because the right turn has no capacity as described above), the program should combine the input flows for both movements to compute the input flow to the combined link. The existing version of the AAP subtracts the input flow to the right and left turns from the upstream through input flow when calculating the input flow to the combined link. A correction was made in the experimental version such that only the input flow to the left turn was subtracted.

2. When generating a TRANSYT-7F file from an AAP data set, it was found that when an intersection had six phases, the program always subtracted a time equal to the clearance interval from the green time of the longest phase in the cycle. This problem was corrected in an experimental version of the AAP.

3. Release 3 of the AAP program has the capability of getting the signal timing from a Graphic Display File (GDF), produced from a TRANSYT-7F or a PASSER-II run, into a base AAP data file. The GDF must represent exactly the same system as that represented by the base AAP file. This capability is very useful when evaluating previous PASSER-II or TRANSYT-7F designs using TRANSYT-7F. However, the

following two difficulties were experienced when working with this feature.

a. The program was unable to get GDFs produced from runs made using Release 6 of TRANSYT-7F. However, it was able to get GDFs obtained from runs made using previous releases of TRANSYT-7F or from PASSER-II[84]. This problem was corrected in an experimental version of the AAP.

b. Timing data in a GDF is expressed as percent of cycle. Thus, the AAP gets the timing in percents of cycle rather than in seconds. However, it will ultimately map the timing in seconds when generating TRANSYT-7F input files. Due to the round-off in the calculation required to transfer from percents to seconds, sometimes the AAP found that the signal timing of a phase was below its minimum when trying to generate a TRANSYT-7F input file. This resulted in the program being unable to generate the TRANSYT-7F file. To make the program work, it was necessary to reduce the minimum green in the AAP data set by one second for the phases that had this problem.

4. When generating TRANSYT-7F files, the minimum greens mapped by the AAP need a correction when overlap phases are involved. When generating a TRANSYT-7F input file for a simulation run, the AAP mapped a minimum green for the overlap phase equal to the actual time coded for the phase. This should be corrected to map the same minimum

green as that mapped when generating a TRANSYT-7F file for an optimization run.

Problems Associated with the PASSER-II Program

PASSER-II was used when determining the thresholds for designing the offsets, producing initial timings for TRANSYT-7F runs, selecting the phase sequence and comparing the progression of the existing sequence with the optimum sequence.

The most recent version of the program is PASSER-II[87] (56). However, the official versions used by AAP, Release 3, is still PASSER-II[84].

PASSER-II[87] has many new capabilities compared with PASSER-II[84] (57). However, experience with PASSER-II[87] indicates that it still has several problems.

Problems with PASSER-II[87] have been documented by the center for Microcomputers in Transportation (McTrans), University of Florida. These problems were observed by users during their work with the program. The following is a list of these problems obtained from communication with McTrans.

1. PASSER-II[87] occasionally extended the through-band through red intervals.

2. The program reported illogical delay for left turn movements. For example, in one situation the program reported a delay of 608.4 sec/veh.

3. Sometimes left turns that had been coded as "without bay" were changed by the program to "with bay."

4. The program did not calculate the level of service for the movement that had no bay.

5. The program gave fatal error messages for minor problems.

Because of these difficulties and because of the need to use the AAP to achieve the productivity required by this study, it was decided to use PASSER-II[84] rather than PASSER-II[87].

When trying to optimize the phase sequence for an artery using PASSER-II[84], the optimum phase sequence for one of the intersections included a lead-lag sequence with a left turn overlap phase. Normally, the overlap phase in the lead-lag sequence is a through phase. A left turn overlap phase is not normally implemented in the field. This type of phase sequence also resulted when running PASSER-II[87] for the same data set. In addition, when examining the GDF produced by PASSER-II[84] for the system, the lead-lag sequence with the left turn overlap phase, described above, was reported as a lead-lag sequence with a through overlap phase. Thus, when the AAP was used to get the timing from this PASSER GDF, it did not result in the correct design sequence.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

This dissertation has presented a new methodology for determining the thresholds for changing signal timing plans in a computer based traffic control system. Currently, these thresholds are determined by judgment. This may result in the implementation of plans which are not the best suited for the measured conditions.

The threshold determination methodology requires the use of available off-line signal timing programs. The methodology also requires the estimation of the turning movement volumes in the system based on detector measurements. Two models have been developed for the purpose of volume estimation in this study. The first is referred to as the estimated variation model and the second as the assumed variation model.

Conclusions

The methodology developed in this study can be used to determine the transfer thresholds for the TRSP operation of the computer based traffic control system investigated. The application of this methodology should improve the system operation by replacing the element of judgment by a more objective technique. The conclusions listed below are offered as a result of this study.

1. The literature review indicates that no work has been done in the area of determining the transfer thresholds for computer based traffic control systems.

2. An essential requirement for traffic responsive operations of the type investigated in this study is the existence of good correlations between the movements in any given direction.

3. The method used for the offset threshold determination is dependent on whether the TRSP selection of splits is disabled on some intersections in the system or not.

4. Disabling the TRSP selection of split plans is preferred at a given intersection if the cross street volumes at that intersection are light, not well correlated with the cross street detectorized approaches, or do not vary much during the day. Disabling the TRSP selection of split plans is also preferred when there are heavy left turns on the artery at the intersection.

5. The assumed variation model is easier to implement than the estimated variation model. The estimated variation model requires the use of more complicated stochastic techniques for estimating nondetectorized approach volumes from detector volumes.

6. The cycle length, the offsets and the splits are selected independently in the TRSP strategy investigated in this study. This is a limitation of this strategy. Ideally

the signal timing parameters should be optimized simultaneously to obtain the best performance of the system.

7. The cycle transfer thresholds obtained based on the assumed variation model are very close to those obtained based on the estimated variation model.

8. The transfer thresholds between offset plans designed using TRANSYT-7F are dependent on the choice of the model used to estimate the turning movement volumes in the system from detector volumes.

9. TRANSYT-7F cannot be used to evaluate PASSER-II designs for threshold determination because TRANSYT-7F and PASSER-II have different design strategies.

10. At the balanced volume condition, the TRANSYT-7F offset design may favor one arterial direction at the expense of the other. This seems to be a function of the arterial volume level and thus the cycle length.

11. The transfer thresholds between offset plans and those between split plans are dependent on the design cycle length selected.

12. There are deficiencies in the application of the permitted movement model in TRANSYT-7F. These deficiencies affect the performance of the plans selected.

13. The adjustment of the input flow rates to sum to the total flow rate of the link in the TRANSYT-7F program needs some modification.

14. Problems are identified with the AAP program. These inconsistencies are related to the treatment of the right turns that have no capacity, mapping the green times, getting the signal timing from a GDF, and mapping the minimum greens.

15. PASSER-II[87] has several difficulties that affect its performance.

16. The PASSER-II[84] program selects a phase sequence which is not normally implemented in the field. In addition, that phase sequence is not reported correctly in the GDF produced by the program.

Recommendations

Several recommendations have emerged from this study. These recommendations fall into the following four areas:

1. Improvements in the TRSP strategy of the closed loop system investigated in this study.

2. Further improvements in the threshold determination methodology.

3. Treatments of the problems identified in the off-line signal timing programs.

4. Further research for TRSP selection of timing plans is warranted.

The transfer thresholds obtained in the examples presented in this study cannot be applied in the field because of the hypothetical involvement of these examples. However, the threshold determination methodology has been

used to determine the transfer thresholds for an arterial system in Gainesville, FL. These thresholds have been determined based on the assumed variation model. The design results will be implemented in Gainesville, FL, in the near future.

Closed Loop System Improvements

Currently, the transfer thresholds for the cycles, the offsets, and the splits are programmed independently in the system master. The results presented in this dissertation indicated that the offset and the split thresholds are dependent on the cycle length selected. It is believed that the closed loop system software should be modified to allow programming different offset and split transfer thresholds for different design cycles.

In addition, it is thought that the offsets and splits for a given cycle should be selected simultaneously to obtain the best results. These two parameters are optimized simultaneously in the TRANSYT-7F program. Thus, it is recommended that the TRSP selection of the split plans (based on cross street detector measurements) should be made dependent on the cycle and offset in effect.

Model Improvements

Several improvements are suggested concerning the threshold determination model as listed below.

1. It has been found that the least squares adjustment model presented in this study needs some

improvement. An alternative method can be suggested for obtaining the weight matrix. In this method, the weight of a link volume is assumed to be inversely proportional to the link volume. Better results have been obtained using this method as compared to the method presented earlier in this dissertation. The details of the proposed improvement is presented in Appendix C.

2. Balancing the input flow and output flows for each internal approach in the system is needed when using the estimated variation model. The least squares adjustment model is used for this purpose. As an alternative, the maximum likelihood method developed by Van Zuylen and Willumsen (42) can be used to balance the count data. However, this method should be modified to balance the input flows and the output flows for each internal approach rather than for each node in the system.

3. Balancing the input and output flows is needed partly because of counting errors and partly because counts may be carried out on different days. If reliable counts are taken concurrently (on the same day) at all intersections, data adjustment would not be needed. In this case, better estimates of the turning movement volumes are expected using the estimated variation model. Also, the use of the estimated variation model will be less complex.

4. Better transfer thresholds might be produced, if the user excludes the minor links from the PI calculation.

In this case, the model will focus on the major links when obtaining the thresholds.

<u>Off-line Model Treatments</u>

It is recommended that the problems identified in the off-line signal timing programs in this study should be solved. These problems affect the performance of these programs.

This study shows that the proposed solutions to the permitted movement model problem in TRANSYT-7F increases the computer time significantly. When deciding on a solution to this problem, special consideration should be given to the increase in the computer time. This increase should be as small as possible.

<u>Recommended Future Research</u>

The last set of recommendations includes areas warranting further research. Specific topics of such research are listed below.

1. The performance of any TRSP strategy in the field is dependent on how well the system sensors have been located. Detectorization must be capable of providing the information required by the TRSP strategy. Without adequate information, the system would not be able to select plans best suited to existing traffic conditions. Currently, there are no guidelines for the location or number of system sensors for the TRSP mode of computerized traffic control systems. Detectors are placed according to the judgment of

the system designer. This sometimes is inadequate to identify the traffic patterns in the system accurately. The surveillance requirements might be dependent on the type of the TRSP strategy implemented. For example, the surveillance requirement for the UTCS-1GC might be different from that for the closed loop systems. Research on the placement of system sensors is therefore required.

2. An investigation is required to evaluate how well the estimated and the assumed variation models are able to estimate the turning movement volumes in the system. Such investigation requires an extensive amount of data collection. Typically, 15-minute counts should be collected for all the system approaches concurrently (on the same day). Count collections should be repeated for different days which would permit the comparison of the volume estimated based on the models discussed in this study with the actual measurements in the field.

3. The TRSP strategy, investigated in this study, involves special pattern selection procedures. Special patterns can be selected based on queue and occupancy detector measurements. Research is needed to develop a methodology for determining the occupancy and queue level above which the special patterns should be implemented.

4. More research is needed to study the conditions for which the signal timing parameters should be designed.

5. In this study general rules are suggested to decide whether the TRSP split plan selection at a given intersection is beneficial. Further research is required in this area.

6. TRSP strategies are considerably more expensive to implement than TOD strategies. Thus, the primary requirement for any TRSP strategy is that it must provide better performance than off-line methods. Research is needed to estimate the potential benefits of these strategies.

APPENDIX A
DERIVATION OF THE LEAST SQUARES ADJUSTMENT MODEL

A least squares adjustment model was derived to adjust the count data such that a balance between the input flow and the output flow for each internal approach in the system could be obtained. Of the different adjustment methods, the least squares method is by far the most common. Since its first application to an astronomical problem by C.F. Gauss, the least squares method has been introduced and applied in many fields in science and engineering (45,46). Its practical importance has been enhanced by the introduction of computers, by the formulation of its techniques in matrix notation, and by connecting its concept to statistics.

The least squares principle ensures that any variation in the observations necessitated by the existence of inconsistencies with the model must be as small as possible taking into consideration the variable weights and subjected to the constrains of the problem (45,46).

In mathematical notation the least squares principle is

$$\text{Minimize } P = V^t W V \qquad \text{(A.1)}$$

where

V = the vector of the residuals and is equal to the adjusted variable minus the unadjusted variable,

W = the symetrical weight matrix of variables, and

V^t = the transpose of the V matrix.

The least squares adjustment model is a mathematical model. Mikhail and Ackermann (45) considered the model to be composed of two parts: the functional model and the stochastic model. The functional model describes the deterministic properties of the physical situation or event under consideration. A set of mathematical equations, referred to as condition equations, is written to describe the functional model of the adjustment problem.

The stochastic model describes the nondeterministic properties of the variables. Let the conditions equation of the functional model take the general form

$$A\ (L + V) = D \qquad \text{(A.2)}$$

where

A = the coefficient matrix,

D = the column vector of constants,

L = the vector of the observational values (unadjusted counts), and

V = the vector of residuals.

Rearranging equation (A.1) leads to

$$AV = F \tag{A.3}$$

with

$$F = D - AL \tag{A.4}$$

A unique least squares solution for equation (A.2) is obtained by adding the least squares criterion:

$$\text{minimize } P = V^tWV$$

If K represents the Lagrange multiplier, we should seek to minimize the following function

$$P_x = V^tWV - 2K^t\,(AV - F) \tag{A.5}$$

To minimize P_x, its derivative with respect to V is equated to zero, and we get

$$\frac{dP_x}{dV} = 2V^tW - 2K^tA = 0^t \tag{A.6}$$

Transposing and rearranging yields

$$-WV + A^tK = 0 \tag{A.7}$$

realizing that W is a symmetric matrix.

Combining equations (A.3) and (A.7) yields

$$\begin{bmatrix} -W & A^t \\ A & O \end{bmatrix} \begin{bmatrix} V \\ K \end{bmatrix} = \begin{bmatrix} O \\ F \end{bmatrix} \tag{A.8}$$

This system of equations, referred to as the total system of normal equations, may be solved directly for V and K. However, for large problems, solution by partitioning is preferred. The solution by partitioning is as follows:

$$V = W^{-1} A^t K = QA^tK \tag{A.9}$$

substituting in equation (A.3) gives

$$AQA^tK = F \tag{A.10}$$

Let

$$Q_e = AQA^t \tag{A.11}$$

substituting in equation (A.11) and solving for K, we obtain

$$K = Q_e^{-1}F \tag{A.12}$$

Vector K is substituted into equation (A.9) to evaluate vector V.

Finally, the least squares estimates of the count volumes can be determined by adding the residuals to the given unadjusted counts.

APPENDIX B
ESTIMATION OF THE PARAMETERS IN MULTIPLE LINEAR REGRESSION MODELS

The linear relationship in the multiple linear regression model can be estimated and tested by estimating and testing the parameters in the model

$$Y = \beta_0 + \beta_1 X_1 + . . . + \beta_j X_j + . . . + \beta_m X_m + E \qquad (B.1)$$

In this equation

Y = the dependent variable,

X_j = the jth independent variable,

β_j = the jth parameter of the model, and

E = the random error.

In the above equation, a parameter β_j is interpreted as the expected change in Y corresponding to a unit change in X_j given that all other Xs are held constant. To derive an estimate for the model parameters, the principle of least squares is applied to a set of n observed values of dependent and independent variables (48).

Defining the Y vector, the X matrix, and the E vector as follows:

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ \cdot \\ y_i \\ \cdot \\ \cdot \\ \cdot \\ y_n \end{bmatrix} \tag{B.2}$$

$$X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdot\ \cdot\ \cdot & x_{1m} \\ 1 & x_{21} & x_{22} & \cdot\ \cdot\ \cdot & x_{2m} \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \\ 1 & x_{i1} & x_{i2} & \cdot\ \cdot\ \cdot & x_{im} \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \\ 1 & x_{n1} & x_{n2} & \cdot\ \cdot\ \cdot & x_{nm} \end{bmatrix} \tag{B.3}$$

$$E = \begin{bmatrix} e_1 \\ e_2 \\ \cdot \\ \cdot \\ \cdot \\ e_i \\ \cdot \\ \cdot \\ \cdot \\ e_n \end{bmatrix} \tag{B.4}$$

where y_i and x_{ij} are values of Y and X_j in the ith observation and e_i is the random error in the ith observation.

Then, the model in matrix notation is

$$Y = XB + E \tag{B.5}$$

where B is the parameter vector. By ignoring the error vector and multiplying both sides of this equation by X^t, one obtains the equations

$$X^tY = X^tXB \tag{B.6}$$

These are called the normal equations. Solution of these equations provides an estimate of B.

$$B = (X^tX)^{-1}X^tY \tag{B.7}$$

APPENDIX C
AN ALTERNATE METHOD FOR OBTAINING THE WEIGHT MATRIX IN LEAST SQUARES ADJUSTMENT

A least squares adjustment model has been used in this study to balance the input and output flows for each internal approach in the system. One of the inputs to the model is the weight matrix. In the theory of adjustment, the term weight has been used to express the precision by way of inverse relation. In Chapter Three, the inverse of the variance-covariance matrix, obtained based on count data, was used to represent the weight matrix. In this appendix, an alternate method for obtaining the weight matrix is suggested.

If the observed counts on a link are assumed to have a Poisson distribution, then their variance equals their mean. This suggests that if the volume on a given link for a given time period is high then its variance for that time period is also high. Thus, its weight is low because it varies more. From the above discussion, it can be suggested that the weight of each count is assumed to be equal to the reciprocal of the count volume.

The least squares adjustment using this new method for obtaining the weight matrix, was tested. Less disturbance

to the original data was observed as compared to the method presented previously.

Example

The same example used in Chapter Three to illustrate the least squares adjustment model concept is used here to illustrate the modification suggested in this appendix. The turning movement volumes in the arterial system before the adjustment is shown in Figure C.1 (a). The functional model of the adjustment problem in the east direction was represented by equations (3.10) and (3.11). For the east direction, the F vector was calculated in Chapter Three to be

$$F = \begin{bmatrix} -44 \\ 0 \end{bmatrix}$$

the A matrix was

$$A = \begin{bmatrix} 1 & 1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

and the vector of the count data before the adjustment was

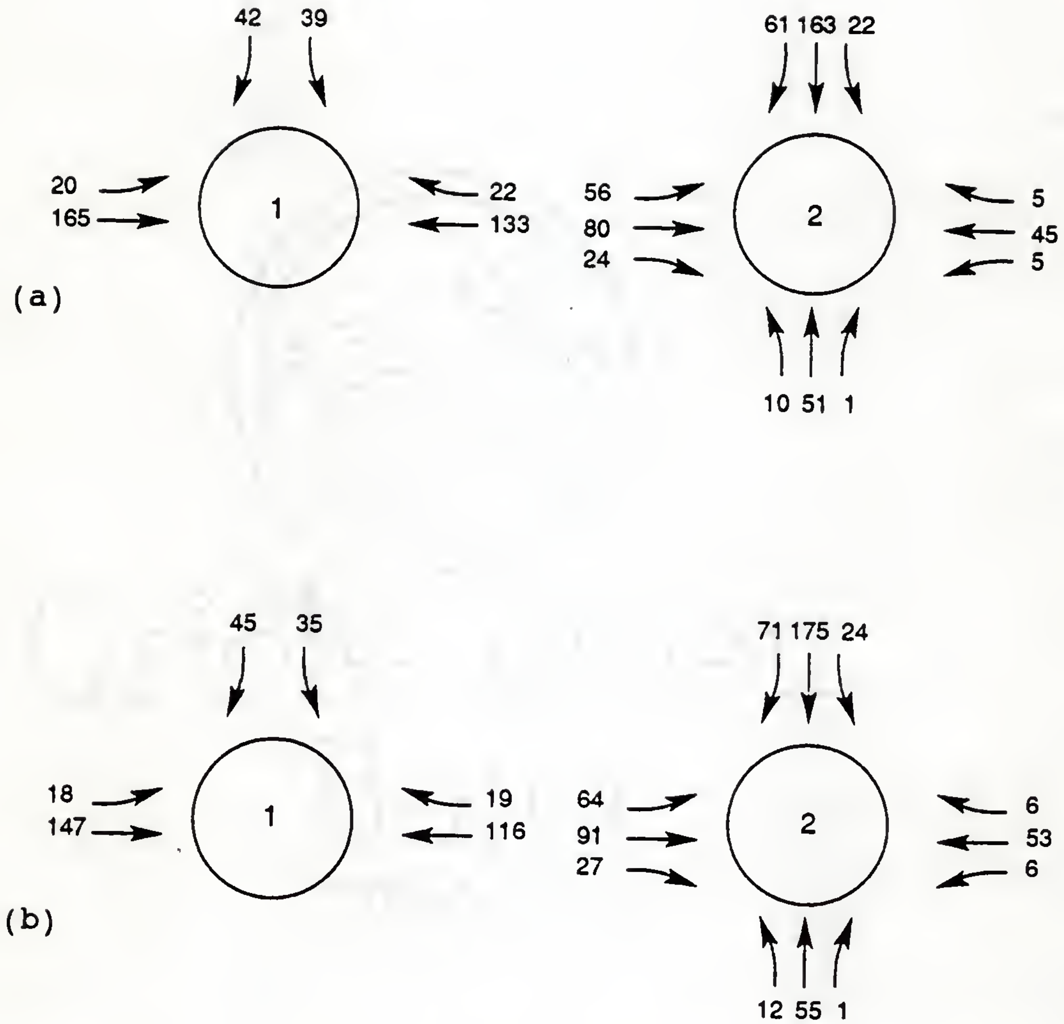

Figure C.1. The adjustment of the turning movement volumes for a two-intersection arterial system in Gainesville, FL, using the alternate method of calculating the weight matrix.

(a) The turning movement volumes in the arterial system before the adjustment.

(b) The turning movement volumes in the arterial system after the adjustment.

$$L = \begin{bmatrix} 165 \\ 39 \\ 56 \\ 24 \\ 80 \end{bmatrix}$$

The inverse of the weight matrix, obtained according to the method suggested in this appendix, is

$$Q = \begin{bmatrix} 165 & 0 & 0 & 0 & 0 \\ 0 & 39 & 0 & 0 & 0 \\ 0 & 0 & 56 & 0 & 0 \\ 0 & 0 & 0 & 24 & 0 \\ 0 & 0 & 0 & 0 & 80 \end{bmatrix}$$

Q, A, and A^t were substituted in the following equation to obtain the Q_e matrix

$$Q_e = AQA^t$$

The following results were obtained:

$$Q_e = \begin{bmatrix} 364 & 44 \\ 44 & 364 \end{bmatrix}$$

and

$$Q_e^{-1} = \begin{bmatrix} 0.0028 & -0.0004 \\ -0.0004 & 0.0028 \end{bmatrix}$$

$$K = Q_e^{-1}F$$

$$= \begin{bmatrix} 0.0028 & -0.0004 \\ -0.0004 & 0.0028 \end{bmatrix} \begin{bmatrix} -44 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} -0.122 \\ 0.016 \end{bmatrix}$$

The vector of residuals, V, was calculated as follows:

$$V = QA^tK$$

Substituting for Q, A^t, and K in the above equation and multiplying resulted in

$$V = \begin{bmatrix} -18 \\ -\ 4 \\ +\ 8 \\ +\ 3 \\ +11 \end{bmatrix}$$

The adjusted count data could then be calculated as

$$L_a = \begin{bmatrix} 165 \\ 39 \\ 56 \\ 24 \\ 80 \end{bmatrix} + \begin{bmatrix} -18 \\ -\ 4 \\ +\ 8 \\ +\ 3 \\ +11 \end{bmatrix} = \begin{bmatrix} 147 \\ 35 \\ 64 \\ 27 \\ 91 \end{bmatrix}$$

The vector of residuals was calculated for the movements in the west direction in a similar manner; the following results were obtained

$$V = \begin{bmatrix} -17 \\ -\ 3 \\ +10 \\ +\ 2 \\ +\ 8 \end{bmatrix}$$

and the adjusted counts in the west direction were calculated as follows:

$$L_a = \begin{bmatrix} 133 \\ 22 \\ 61 \\ 10 \\ 45 \end{bmatrix} + \begin{bmatrix} -17 \\ -\ 3 \\ +10 \\ +\ 2 \\ +\ 8 \end{bmatrix} = \begin{bmatrix} 116 \\ 19 \\ 71 \\ 12 \\ 53 \end{bmatrix}$$

The movements that were not included in the least squares adjustment calculation presented above were adjusted using the method described in Chapter Three. The turning movement volumes in the system after the adjustment are shown in Figure C.1 (b).

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BIOGRAPHICAL SKETCH

Mohammed Abdul Hasan Hadi was born in the city of Hilla, Babylon, Republic of Iraq, on November 3, 1956. He graduated from Central High School in Baghdad, Iraq, in 1974.

In September, 1974, he enrolled at the University of Baghdad where he studied civil engineering. He was awarded the Bachelor of Science in June, 1978.

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In 1983, he accepted a position as a research assistant at the Building Research Center, Council for Scientific Research in Baghdad, Iraq. During his work at the Center, he was involved in a number of research projects in the fields of soil stabilization and building materials. He was coauthor of a number of articles in these subjects. In 1984, Mr. Hadi was designated as one of the best researchers in the Council.

In 1986, he was awarded a scholarship from the Iraqi government to continue his education toward a doctoral degree in traffic engineering.

In June 1986, Mr. Hadi entered the Graduate School of the University of Florida, where he pursued the degree of Doctor of Philosophy in civil engineering, specializing in transportation and traffic engineering. During the course of his academic work, he has been involved in a number of transportation research projects.

Mr. Hadi is married to Nada Amer Salbi.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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